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Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities

Volume 4. Offshore of Newfoundland and Labrador

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PREFACE

This document is Volume 4 of a series of reports entitled "Geological Evolution and Analysis of Confirmed or Suspected Gas Hydrate Localities." Volume 4 is an analysis of the "Formation and Stability of Gas Hydrates Offshore of Newfoundland and Labrador." This report presents a geological description of the offshore regions of Newfoundland and Labrador, including regional and local structural settings, geomorphology, geological history, stratigraphy, and physical properties. It provides the necessary regional and geological background for more in-depth research of the area. Detailed discussion of bottom simulating acoustic reflectors, sediment acoustic properties, and distribution of hydrates within the sediments. The formation and stabilization of gas hydrates in sediments are considered in terms of phase relations, nucleation, and crystallization constraints, gas solubility, pore fluid chemistry, inorganic diagenesis, and sediment organic content. Together with a depositional analysis of the area, this report is a better understanding of the thermal evolution of the locality. It should lead to an assessment of the potential for thermogenic hydrocarbon generation.

Project Manager
Gas Hydrates

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BASIN ANALYSIS, FORMATION AND STABILITY OF GAS HYDRATES IN THE OFFSHORE OF NEWFOUNDLAND AND LABRADOR

By Jan Krason and Bernard Rudloff

EXECUTIVE SUMMARY

Among twenty-four gas hydrate sites confirmed or inferred from offshore of oceanic regions of various parts of the world (Kvenvolden and McMenamin, 1980; and Malone, 1982), one is located within the eastern Canadian Continental Margin (Taylor et al., 1979; Judge, 1980). The bathymetric, geomorphologic, and geologic environments of this large region are complex. Basin analysis, the study of geological relationships to gas hydrate formation and stability, presented in this report covers approximately 900,000 km^2 offshore of Newfoundland and Labrador.

Although this study is based on published literature and relevant data readily available, the study results lead to a general conclusion that offshore Newfoundland and Labrador are indeed areas with environments favorable for gas hydrate formation and stability. It can also be concluded from this study that neither offshore Newfoundland nor Labrador should presently be considered as prime gas hydrate regions. Nevertheless, with regard to both general conclusions, it should be noted that during the course of study, two major hindrances have been encountered: 1 - there is scant evidence for gas hydrate occurence; so far only one seismic bottom simulating reflector (BSR) has been reported in the literature (Taylor et al., 1979), and 2 - most of the seismic survey data are being held as proprietary.

There are also geomorphologic and bathymetric environments unfavorable for biogenic gas hydrate formation and stability since a very large area of the study region is covered by shallow shelf water (shallower than 200 m). Areas covered by shallow water include the Grand Banks of Newfoundland and the Labrador Shelf. For both, geologic information is abundant.

The sedimentary basins under the continental slope and upper rise (1,000 - 3,500 m water depth) have been poorly tested for oil and gas deposits; for these areas there is a severe lack of data.

This study shows that the eastern Canadian Continental Margin underwent epeirogenic deformation and fragmentation during Early Cretaceous time. Major tectonic deformation occurred 100 m.y. after the initial rifting phase. The tectonic events led to the development of a complex sedimentary basin pattern and a major "Early Cretaceous Avalon Unconformity".

At the same time, the outer periphery of the eastern Canadian Continental Margin was affected by large scale disjunctive deformation and the foundering of large blocks of the crystalline basement at bathyal depth.

Tectonic activity influenced the present complicated configuration of the continental slope and produced a complex array of basins and highs. Also, the Labrador Shelf underwent initial rifting in Cretaceous time.

The final phase of the entire geologic evaluation of the margin is similar in its main outlines to the evaluation of the U.S. part of the Atlantic Continental Margin. The entire shelf edge from the southern Grand Banks to northern Labrador prograded steadily throughout the Tertiary and Quaternary, leading to seaward progradation by a successive development of large, steep, unstable clastic aprons over the upper part of the continental slope.

A very large amount of sand and mud was redeposited by a gravity driven process (i.e. slumping, sliding, and turbidity currents) from the shelf edge and upper slope to the deep water area of the lower slope.

In the same parts of the study region, in east Newfoundland Basin and the southernmost Labrador Shelf, the present oceanic bottom temperature and hydrostatic pressure are conducive to gas hydrate development, and turbidite slumping lithologic assemblages are regarded as especially favorable for gas hydrate formation and stability.

Gassy black muds of late Pleistocene age are documented at the Labrador Shelf, but the Grand Banks of Newfoundland are covered with only a thin veneer of gravelly material and therefore not considered favorable for bacterial methane gas generation.

Data from the Deep Sea Drilling Project (DSDP) indicate that the organic material in the sedimentary sequence (Cretaceous through Holocene) is oxidized and present in variable amounts. Obviously this is an unfavorable factor for gas hydrate formation and preservation. The organic content of the Pleistocene age sediments in the Labrador Sea appear to be dominated by glacially derived, degraded organic matter of terrestrial origin with limited capacity for bacterial generation of gas. This means that the gas hydrate potential within the turbidite type sediment, in the bathyal part of the basin, may also be also limited. However, a weak seismic reflector in the Tertiary section with a configuration and subbottom depth consistent with it being a possible BSR was located in the Labrador Sea.

There is no information pertaining to the flux of recent sediments and biogenic generation of gas in the continental slope. However, assuming that in this sedimentary environment there is higher marine organic matter productivity and that there is only a moderate dilution by clastic material, the continental slope could be considered as having the highest gas hydrate potential. A single BSR was already reported from this environment, at a water depth of 2000 m of ocean water (Taylor et al., 1979).

Thermogenic gas has been reported from pre middle Cretaceous age reservoirs in northern Grand Banks (Hibernia oil and gas field, and others). The reservoirs are sealed by a thick post-Avalon Unconformity sedimentary sequence; upward gas migration does not seem to be a likely source of methane for gas hydrates except possibly near salt diapirs. However, no BSR has been reported from the top of any salt structure.

At the Labrador Shelf, natural gas has been found in the Cenozoic age reservoirs above elevated basement structures. In this case, it has been inferred that the gas migrated laterally from thermally mature sediments on the continental slope.

Data relevant to this study are summarized in Table 1.

Because of locally highly favorable environments, but insufficient data, a more confident assessment of gas hydrate potential in offshore Newfoundland and Labrador would require the following:

Table 1. SUMMARY DATA OF BASIN ANALYSIS, FORMATION AND STABILITY OF GAS HYDRATES OFFSHORE OF NEWFOUNDLAND AND LABRADOR

FACTORS / BASIN	CONTINENTAL MARGIN OF OFFSHORE NEWFOUNDLAND	EAST LABRADOR BASIN AND SOUTHERNMOST LABRADOR SHELF	OFFSHORE LABRADOR
SUB-BASIN	GRAND BANKS, FLEMISH BASIN, NEWFOUNDLAND RIDGE, J-ANOMALY RIDGE		LABRADOR SHELF AND LABRADOR SEA
BASIN ANALYSIS			
Location			
Longitude: latitude	44°W - 56°W: 40°N - 48°N	46°W - 54°W: 48°N - 53°N	40°W - 64°W: 52°N - 62°N
Areal extent, km²	500,000 km²	300,000 km²	600,000 km²
Geomorphology	Continental shelf and slope	Continental shelf and slope	Continental shelf, slope, rise, Abyssal Plain
Geomophologic sub-unit	Mid-slope basin, contour current ridge	Mid-slope basin, submerged knoll	Submarine canyons, contour current ridges
Geology	Well known	Moderately known	Moderately known
Structural setting	Rifted continental crust	Downwarped basin in rifted continental crust	Rifted continental and oceanic crust
Stratigraphy	Triassic through Quaternary	Triassic through Quaternary	Triassic through Quaternary
Lithology	Clastics, carbonates; glacial drift	Clastics	Clastics
Sedimentary environments	Mainly marine - hemipelagic	Mainly marine - hemipelagic and glacial	Mainly marine - hemipelagic and pelagic, glacial
Sediment source	Canadian Craton; Authigenic carbonates	Canadian Craton	Canadian Craton, Iceland
Rate of sedimentation	Mean of 10 m/m.y.; Authigenic carbonates	0.6 m/m.y. DSDP Site 111	Undetermined
Sediment flux, mg/cm²/yr	Undetermined	Undetermined	3 - 7 mg/cm²/yr DSDP 112; 16 - 57 mg/cm²/yr DSDP 113B
Organic matter flux, mg/cm²/yr	Undetermined	Undetermined	Undetermined
Geochemistry	Poorly known	Poorly known	Moderately known
Total organic matter content, weight %	< 0.1% at DSDP Site 389	Unknown	0.3 - 0.5% on shelf, < 0.5 in Labrador Sea
Source of organic matter	Terrestrial in Mezoz.; marine in Cenoz.; terrestrial in Holocene	Marine in mature zone	Terrestrial
Preservation of organic matter	Undetermined	Undetermined	Poor to good
Depth of thermal maturity, m	3,000 m	3,000 m	2,500 m
Geochemical anomalies	Undetermined	Undetermined	High SO_4^{-2} concn. at depth
Sediment alteration	Undetermined	Undetermined	Undetermined
Physical and geophysical features	Moderately known	Moderately known	Moderately known
Thickness, m	1,000 - 12,000 m	8,000 - 14,000 m	2,000 - 10,000 m
Porosity	10% - 50%	10% - 50%	10% - 50%
Permeability, md (millidarcy)	Not available	Not available	Not available
Geothermal gradient, °C/m	3°C/100 m	2.7°C/100 m	4°C/100 m
Heat flow, HFU (heat flow unit)	Undetermined	Undetermined	Undetermined
GAS HYDRATES FORMATION AND STABILITY			
Direct evidence	None	None	None
Type of gas hydrate occurrence	Unknown	Unknown	Unknown
Indirect evidence	None	Unknown	BSR in Labrador Sea, gassy muds on Labrador Shelf
Bottom simulating reflector(s), BSR	Unknown	Undocumented BSR possible (Taylor et al., 1979)	Present
Areal extent of the bottom simulating reflector(s), km²	Not applicable	Unknown	< 100 km²
Quality of seismic data	Poor	Poor	Poor
Inferred evidence	Favorable water depth and temp.	Favorable water depth and temp.	Favorable water depth and temp.
Location	Bathymetr. most of the basin	Bathymetr. most of the basin	BSR at 53°20'N - 47°17'W
Sea water depth, m	85 - 4,000 m	1,000 - 3,000 m	200 - 4,000 m
Sub-sea bottom depth, m	20 - 600 m	200 - 600 m	20 - 600 m
Hydrostatic pressure at sea floor, atmosphere	10.5 - 480 atm.; 10.45 kpA/m press. grad.	120 - 480 atm.; 10.45 kpA/m press. grad.	240 - 480 atm.; 10.45 kpA/m press. grad.
Temperature at sea floor, °C	0°C	0°C	0°C
Gas hydrates host formation	Not formalized	Not formalized	Unconsolidated muds
Age of gas hydrates host formation	Pliocene - Pleistocene	Pliocene - Holocene	Tertiary - Pleistocene
Gas hydrates stability zone	80 - 600 m	200 - 600 m	80 - 600 m
Initial porosity of gas hydrates host formation, vol. %	40%	40%	40%
Isotopic composition of gas, ^{13}C %	Unknown	Unknown	Unknown
Pore water salinity, % at depth m	Unknown	Unknown	Unknown
Associated hydrocarbons	Petroleum, natural gas	Condensate and natural gas shows	Natural gas
Time of gas hydrates stabilization	Wisconsin (?)	Wisconsin (?)	Pleistocene - Holocene
Source of gas hydrates	Thermogenic most probable	Thermogenic or biogenic possible	Biogenic most probable
Evidence for free gas under gas hydrate zone	None	None	None
Estimated/inferred gas volume, at 25 °C/atm.			
In gas hydrates	2×10^{10} m³ (0.8 TCF) per 1 m thickness of 5% hydrate	2×10^{10} m³ (0.7 TCF) per 1 m thickness of 5% hydrate	1×10^{11} m³ (3.5 TCF) per 1 m thickness of 5% hydrate
In trapped free gas	No evidence	No evidence	No evidence

1. **Access to proprietary seismic data.** Analysis of a comprehensive suite of seismic sections would allow an accurate determination of possible thermogenic gas sources and migration pathways. Presumably more BSRs could be detected and be evaluated to determine distribution of gas hydrate zones throughout the region.

2. **Access to proprietary drilling results.** Seismic stratigraphic interpretations could be refined with drill hole control. Irregularities in drilling rates and down hole pressures and temperatures may signal hydrate accumulations which are not evident on seismic sections.

3. **Detailed geologic and seismic study of slope and rise regions.** If features similar in form to the Blake Outer Ridge to the south, which has been proven to contain hydrates can be located, the gas hydrate potential of the Labrador and Newfoundland offshore region would be greatly enhanced.

4. **Industry supported research.** Because of the potential of gas hydrates as unconventional energy resources and the possible danger and engineering problems associated with drilling through unrecognized gas hydrate zones, the oil and gas industry should initiate and support research into gas hydrates.

INTRODUCTION

Gas hydrates, although relatively poorly understood, could be of great importance as unconventional and "enormous potential energy resources" (ref. is also made to an official statement by E.A. Kozlovsky, Minister, USSR, Ministry of Geology, during the opening ceremony of the 27th International Geological Congress, held in Moscow, 4-14 August, 1984). However, resources are defined as mineral and/or fossil fuel concentrations amenable to economic development under current or reasonably anticipated conditions. Resources are also defined as deposits inferred to exist but not discovered. Resource estimates are nebulous and cannot be considered as available until actually discovered and reliably assessed. Also, shallow gas hydrate zones within the upper section of the sedimentary column can lead to severe problems in drilling and sediment instability.

The purpose of this study is to provide a systematic assessment of the geological factors favorable for gas hydrate formation and stability factors and resource potential offshore of Newfoundland and Labrador.

The exceptionally large study region has been subdivided into smaller units - based on following geomorphological, depositional characteristics and arbitrary geographical limits (Figure 1).

Geological environments favorable for gas hydrate potential and the application of gas hydrate formation and stability models are still not well understood, particularly within the offshore regions. With a few exceptions (Kvenvolden et al., 1983), gas hydrates have not been properly evaluated.

Therefore, a concept-oriented evaluation of directly and indirectly relevant data was made and the geological environments favorable for gas hydrate formation and resources were assessed. In this study, data base evaluation and the assessment process is primarily based on such basic geologic factors as regional and local structural settings, stratigraphy and paleogeographic development. The presence and characteristics of the hydrocarbon source, geophysical and geochemical conditions of gas hydrate generation and stabilization in each main and subsedimentary basin, were also analyzed.

Because of the previously reported single occurrence of the bottom simulating reflector (BSR; Taylor et al, 1979) offshore of Newfoundland and the inferred presence of gas hydrates by the same authors at the Labrador Shelf, this entire region has been designated by the U.S. Department of Energy - Morgantown Energy Technology Center (DOE-METC) for evaluation. The results of the evaluation by Geoexplorers International, Inc. with regard to the offshore of Newfoundland and Labrador are presented in this report.

In due course of this study, it is emphasized that the bathymetric and geological conditions of some large areas of the eastern Canadian Continental Margin are generally favorable for the formation and preservation of gas hydrates. The presence of a newly discovered giant oil and gas field known

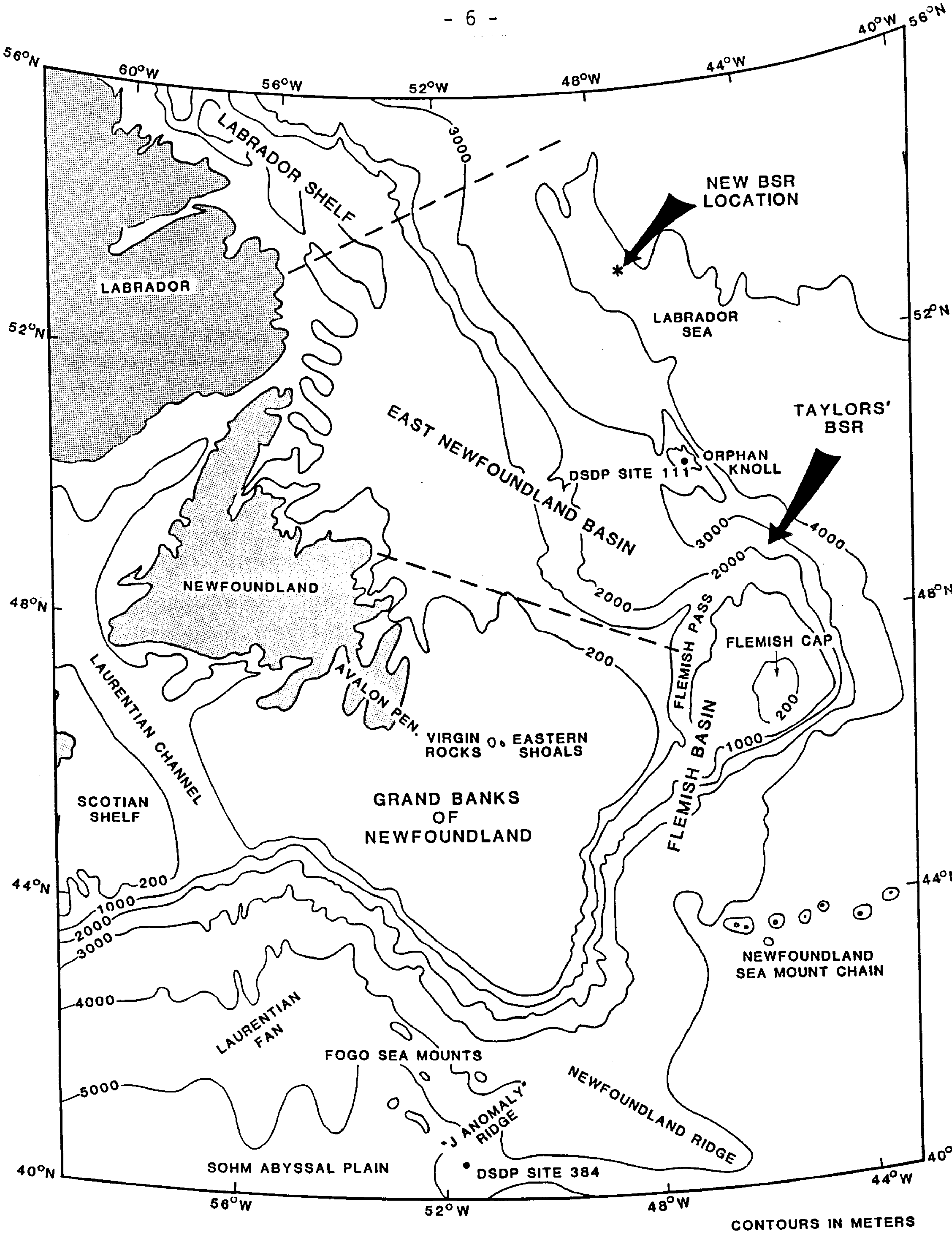

Figure 1. BATHYMETRIC MAP OF OFFSHORE NEWFOUNDLAND AND SOUTHERN LABRADOR

Modified after Laughton et al. (1972)

as Hibernia, offshore Newfoundland (although at a very shallow depth of oceanic water, less than 100 m), and smaller oil fields and numerous hydrocarbon shows in the same region, should also be considered as other factors favorable for the formation of gas hydrates and their resource potential.

However, there are also numerous unfavorable factors which have to be considered in gas hydrate assessment. Perhaps the most important one is the lack of any direct evidence for the presence of gas hydrates in the entire study region except for the degassing of black late Pleistocene glacial muds from the Labrador Shelf. We were also unable to confirm the gas hydrate occurrences previously reported by Taylor et al. (1979) and Judge (1980). There is also a lack of supportive evidence from geophysical surveys. Except for the above mentioned BSR, only one other was detected. However, most of the geophysical data are being held as proprietary and were not available for study.

Thus, a definitive assessment of the gas hydrate potential cannot be provided due to the lack of appropriate data. However, in most of the study region, conditions of sedimentation rate, bottom water temperature, organic matter influx and its type, are probably sufficiently favorable for gas hydrate formation.

Acknowledgements

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PART I

BASIN ANALYSIS

Regional Geologic Synopsis

The northeastern continental margin of the North American continent encompasses large tracts of the northwestern part of the Atlantic Ocean including, among others, offshore of Newfoundland and the Labrador Peninsula. The northern section of the North American Continental Margin differs markedly from the simpler, better studied, U.S. Atlantic Continental Margin. For a brief review of the major geologic features and characteristics of a typical passive continental margin the reader is referred to a separate report by Krason and Ridley (1985b).

The northeastern American continental margin is not only much larger but also geologically more complex. In contrast to the southern margin, a thick Paleozoic pre-rift clastic sedimentary sequence which includes coal beds and a salt and anhydrite unit is present. It experienced the same Late Triassic to Early Jurassic continental breakup, deep crustal attenuation, upper crustal extension and thermal subsidence phase which affected the southern part of the continental margin. A syn-rift clastic red bed sequence deposited in graben-type basins and thick evaporitic sequences characterized that period of geologic evolution. The rift phase did not affect the present Labrador continental margin which became differentiated during Early Cretaceous time.

The Early Jurassic initiated the post-rift phase dominated by tectonic quiescence and steady passive subsidence. A thick deltaic, marginal marine to shelf sequence accumulated during the Jurassic through the Early Cretaceous. The edge of the subsiding continental margin was rimmed during Late Jurassic to Early Cretaceous time by a discontinuous shallow water carbonate platform. The identification of the presently disconnected remnants of this fringing Upper Jurassic to Lower Cretaceous carbonate assemblage in some of the far offshore crustal blocks of the northwestern Atlantic Ocean, such as Orphan Knoll, Flemish Cap, the Fogo Seamounts and the deep oceanic ridge known as the J - Anomaly Ridge is the best documentation of the original seaward edge of the northeastern continental margin.

The salient geologic feature of the Grand Banks and its northern extension within the deep water of the East Newfoundland Basin is a regional angular unconformity, known as the Avalon Unconformity, of Early Cretaceous age. The unconformity separates individual block faulted Jurassic sub-basins and intervening basement highs from a thick, undeformed, blanketlike Upper Cretaceous to Tertiary open shelf marine sequence.

The Late Cretaceous fragmentation of the continental margin, some 100 m.y. after the initiation of the original rifting phase is the major feature of the geologic evolution of the southern part of the American continental margin. Block faulting and differential subsidence patterns ultimately led to the present complex configuration of the continental slope and the large composite, block faulted basins (East Newfoundland Basin and Flemish Basin) which presently lay in deep water. Their geology is inferred to reflect the better known sub-basin geologic configuration and evolution of the Grand Banks.

The Cretaceous epeirogenic event corresponds farther north, at the level of the Labrador Continental Margin to the initial continental breakup, rifting and presumed separation from Greenland. An Upper Cretaceous continental syn-rift sequence was deposited within extensional grabens, accompanied by basic volcanism. The post-rift Labrador sequence, which followed in response to a steady, passive thermal subsidence of the rifted platform rests unconformably (Avalon equivalent unconformity) over the syn-rift assemblage and is composed of an Upper Cretaceous through Tertiary deltaic to marginal marine clastic sequence.

Salt diapirism, and to a limited extent shale diaprisim, is common through the Grand Banks and the western part of the East Newfoundland Basin. The salt diapirs originated from Late Triassic to Early Jurassic salt units and possibly from middle Carboniferous formations. The salt diapirs are regarded as the best conduit for deep, thermogenic upward gas migration to a near sea floor environment and thereby as likely candidates for gas hydrate occurrence.

The Late Tertiary and Quaternary periods witnessed a major change in sedimentary pattern linked to a slowing of subsidence and an increase in clastic sediment influx from the adjacent continent. This pattern of sediment distribution through the Late Tertiary and Quaternary is important because present-day gas hydrates can possibly be expected and presumably be found within these sedimentary units. A transient system of shelf sedimentation developed, with the main depocenters at the shelf edge and upper continental slope of Newfoundland and Labrador. The shelf sedimentary bypass led to shelf margin outbuilding and steady progradation into the deeper waters of the continental slope. This caused widespread instability and gravity induced failure of the clastic aprons. Growth faulting, slope sliding, large-scale slumping, gravity flows and turbidity currents appear to have been the gravity driven resedimentation processes responsible for this major mass transfer from the shelf edge to the lower continental slope and the abyssal realm. Huge amounts of clastic material invaded the lower continental slope, as seismically documented from the margins of the Grand Banks, the East Newfoundland Basin, the Labrador continental slope and the Labrador Basin.

This large sedimentary transfer from the shallow continental shelf to the continental slope accelerated during eustatic lowstands of sea level when the shelf was partly to completely emergent. The present continental shelf is an area of relict sediment distribution involving mostly thin deposits of the last glacial stage, reworked to some extent by the subsequent sea level rise. The majority of the glacial sediments were deposited at the actively prograding shelf edge - upper continental slope and redistributed by submarine mass wasting processes and turbidity currents to the lower continental slope, possibly through submarine canyons which directly funneled large volumes of sand and clay directly to the abyssal realm, interrupting hemipelagic sedimentation.

Thus, the Late Tertiary and Quaternary depositional pattern can have implications for gas hydrate occurrences. The near complete absence of reasonably detailed geologic and sedimentologic data from the present continental slope and the deep bathyal clastic basins (East Newfoundland Basin, Flemish Basin, Labrador Basin) has hampered gas hydrate assessment. Seismic profiles have shown, in a general way, that the upper sedimentary column of some of the segments of the continental slope and of their basins can be interpreted in terms of major slumping and turbidity current processes. The high sedimentation rates associated with these processes can be regarded as discussed by Krason and Ridley (1985a) as favorable for organic matter preservation and thereby biogenic bacterial gas generation. Whether enough organic matter was preserved for methane production is conjectural due to a lack of sample data.

The Continental Margin of Offshore Newfoundland

The continental margin of the northeastern salient of the North American craton of offshore Newfoundland has been documented during the past decade to extend substantially beyond the shallow water area of the Grand Banks of Newfoundland (bounded by the 200 m isobath), and to encompass deeper water areas up to 44° W longitude (Figure 1). The area is constrained, smoothing major salients and embayments, between approximately 44° N to 53° N latitude, and covers approximately 900,000 km^2. The Labrador Shelf beyond latitude 53° N is the subject of a separate discussion.

Flemish Cap, a shallow plateau bounded by the 200 m isobath located approximately 650 km from the Avalon Peninsula of Newfoundland, and Orphan Knoll, a submarine plateau beneath 1,800 m of water located 550 km north-east of Newfoundland, are both floored by continental crust. Seismic studies have shown that the inshore areas of both plateaus up to the edge of the Grand Banks are also of continental character.

The extent of the continental margin of the craton has also been delineated further offshore in deep water (3,000 m - 4,000 m) at the site of the Newfoundland Ridge and the so-called J - Anomaly Ridge.

Each of these submarine plateaus or ridges are described and discussed and integrated into the larger subject of continental margin evolution, particularly with regard to the fragmentation and foundering of the outer periphery at bathyal depths during Late Cretaceous - Paleocene time.

The geological environments most favorable for gas hydrate stabilization appear to be limited to the outer continental slope and rise. Such environments appear to be present on the basis of the theoretical stability data and empirical observation, especially in the Blake Outer Ridge (Krason and Ridley, 1985a) and the Baltimore Canyon Trough (Krason and Ridley, 1985b). Unfortunately, data for the Newfoundland offshore slope environment is sparse compared to the shelf areas of the same region. The large area of the rise between 2,000 m and 3,000 m depth and the northeastern edge of the Grand Banks shelf and Orphan Knoll (East Newfoundland Basin) can be considered favorable, but we again encounter a severe lack of pertinent information. There is probably fairly dense seismic coverage of a proprietary nature unavailable to this study.

The Grand Banks is characterized by very shallow water and a coarse, sandy to pebbly subbottom, without good quality organic-bearing sediments conducive to biogenic methane production and hydrate formation. However, Judge (1980) lists the Grand Banks as having reported hydrate occurrences (Figure 1).

The inferred occurrence of gas hydrates in the slope-rise environment is supported by the identification of a single bottom simulating reflector (BSR) north of Flemish Cap at approximately 2,000 m in water depth. However, the precise locality of the gas hydrate occurence is not specified (Taylor et al., 1979; pers. commun. by Kenard and Coffman, Imperial Oil Ltd.)

Historical Review

Following a number of pioneering studies not reviewed here, the major period of geological and geophysical investigations of offshore Newfoundland dates from the mid-1960s. Interest in the newly formulated plate tectonic theory led to a dramatic growth of marine geology and geophysics. Unfortunately, the conclusions of these studies were based on sweeping generalizations and appear slanted against the possibility of significant amounts of continental crust in offshore areas (Laughton, 1972; Le Pichon et al., 1971 and others).

The second thrust in offshore investigations in the mid-1960s was directly related to the search for petroleum by major oil companies, and to a limited extent by federal and provincial governmental agencies involved in hydrocarbon potential assessment. Consequently, a great amount of important data, particularly seismic profiles, lithologic and wire-line logs are proprietary and only a limited data set has been released in the public domain.

To date, 206 wells have been drilled by oil companies on the Canadian Atlantic margin (Oil and Gas Journal, 1985) although a large number of these wells are located on the Scotian Shelf. Disregarding this area, which is outside of the region designated by DOE-METC for this study, there remains a large number of uneconomic oil and gas shows in the Grand Banks region; and a giant oil field, Hibernia, with reserves confidently estimated to be over 1 billion barrels (Burden et al., 1983; Oil and Gas Journal, 1985) has also been discovered (Figure 2).

Additional information bearing on the lithological nature of the submarine sea floor is available from limited dredging and shallow drilling research programs (Legault, 1982; Lilly, 1965, 1966; Pelletier, 1971; Ruffman et al., 1973).

The geological evolution of the Newfoundland continental margin is outlined, progressing from the Grand Banks to geomorphologic features located progressively offshore and into deeper water. Due to the relative abundance of data pertaining to the evolution of the Grand Banks, it is discussed in more detail than deeper parts of the area. It should be understood that whereas the shallow shelf areas are unlikely to be favorable sites for gas hydrates, their geological history provides insights into the development of the slope and rise areas where gas hydrates are more likely to occur.

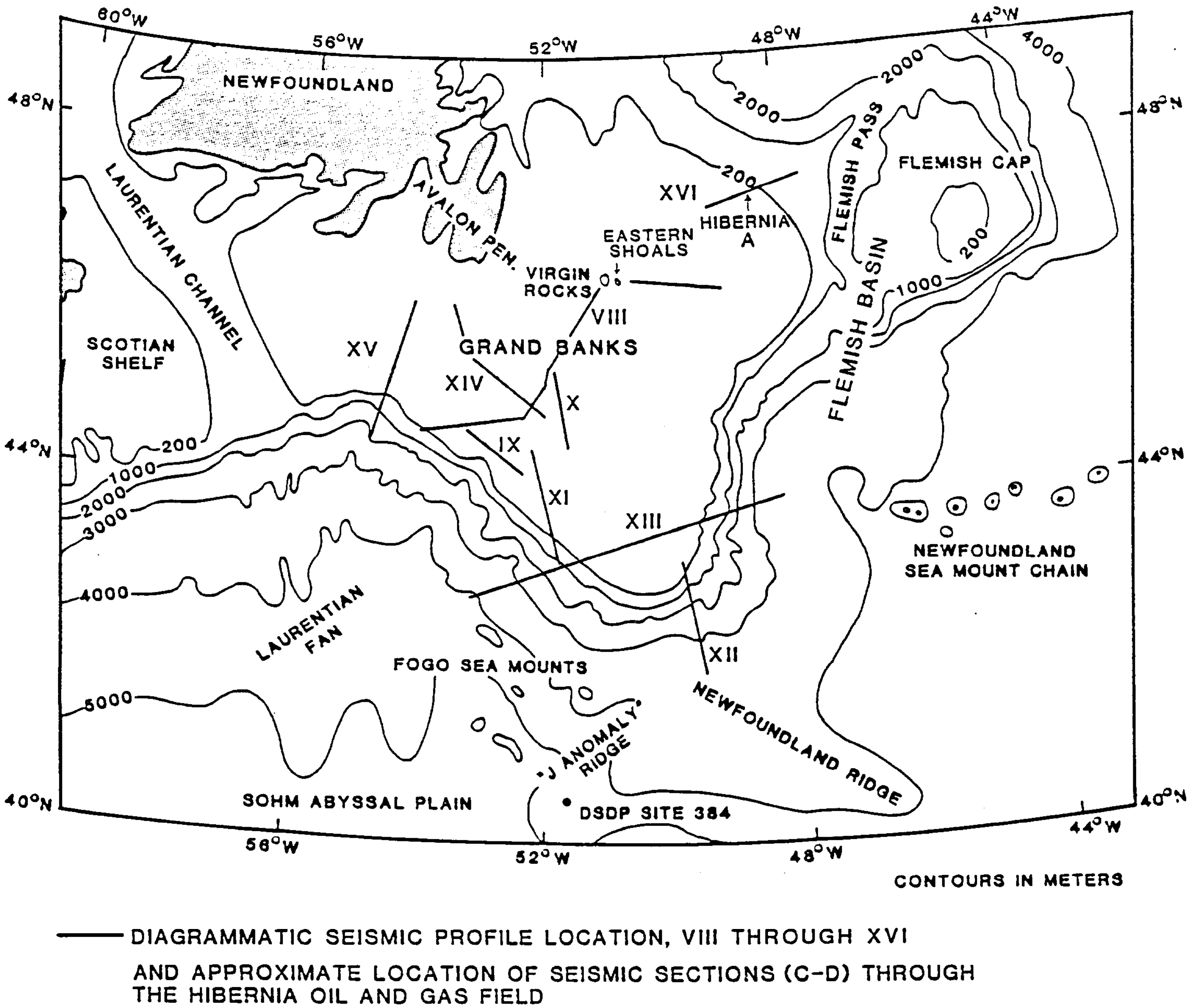


Figure 2. GENERALIZED BATHYMETRIC MAP OF THE GRAND BANKS WITH LOCATION OF DIAGRAMMATIC SEISMIC PROFILES AND SECTIONS

Modified after Laughton et al. (1972)

Tectonics and Stratigraphy

Grand Banks. The Grand Banks of Newfoundland, located to the southeast of Newfoundland, is a vast shallow submarine shelf (100 m average depth), which can be conveniently delineated by the 200 m isobath. The Grand Banks lies between 48° W to 56° W longitude and 40° N to 48° N latitude and covers approximately 300,000 square kilometers (Figure 2). It falls away rapidly in water depths in excess of 2,000 m on its southern and eastern flanks and much more progressively on its northern flank.

In the Grand Banks of Newfoundland, up to 1983, sixty-two oil and gas wells had been drilled in clusters with sparsely drilled intervening areas. Most of the stratigraphic information included in this chapter is derived from these oil and gas wells.

Although seismic profiles are proprietary, the basic information pertaining to the lithology encountered by drilling was released to the public after a few years. This allowed the Jansa and Wade synthesis published in 1975 and the major article published by the geologic staff of Amoco Petroleum Co. Ltd., and Imperial Oil Ltd., in 1973 to be written. Except where otherwise stated, the bulk of the information presented in this section is derived from these two authoritative papers.

The stratigraphic nomenclature used in the Newfoundland Continental Margin was derived, for reasons of precedence and stratigraphic similarity, from the Scotian Shelf area which was studied and drilled slightly earlier.

The submarine bedrock geology reflects a regional dip to the southwest from basement outcrops of the north-central area (Virgin Rocks, Eastern Shoals) to more and more recent subcrop rims (Figure 3).

The southern and central part of the Grand Banks consists of a series of rather narrow, NE-SW trending sub-basins filled with mostly Jurassic sediments up to 6,000 m in thickness. These sub-basins have been labelled, from west to east the Whale, Horseshoe, Jeanne d'Arc (itself the southern narrow prolongation of the much larger and less understood East Newfoundland or Avalon basin) and Carson Sub-basins (Figure 4). These Jurassic sub-basins are fault bounded depressions separated by narrow intervening basement horsts (Figure 5). The southwestern part of the Grand Banks is underlain by the northeastern termination of the large Scotian Basin, known as the South Whale Sub-basin. The southeastern part of the Grand Banks is floored by a large positive feature, known as the South Bank High which was not onlapped until early Late Cretaceous. Further eastward and seaward from the northeastern edge of the Grand Banks occurs a large Cretaceous - Quaternary basin known as the Flemish Basin. Seismic data indicate 6,000 m of sediments under the lower slope of the northeastern Grand Banks. The relationship of the Flemish Basin with the older Carson Sub-basin to the west and the East Newfoundland Basin to the north are obscure. The sedimentary overlap on the Flemish Cap on its east flank has been previously alluded to. This basin is seismically characterized by the absence of salt diapirs.

Basement. The basement of the Grand Banks is known from sea floor outcrops at Virgin Rocks and Eastern Shoals (Figure 3), (Lilly, 1965; 1966) and has also been encountered at the bottom of some wells drilled along the faulted margins of the sub-basins or on top of basement induced structures. The pre-Devonian basement consists of low-grade meta-sedimentary rocks, minor low grade mafic metavolcanics, and granitic rocks.

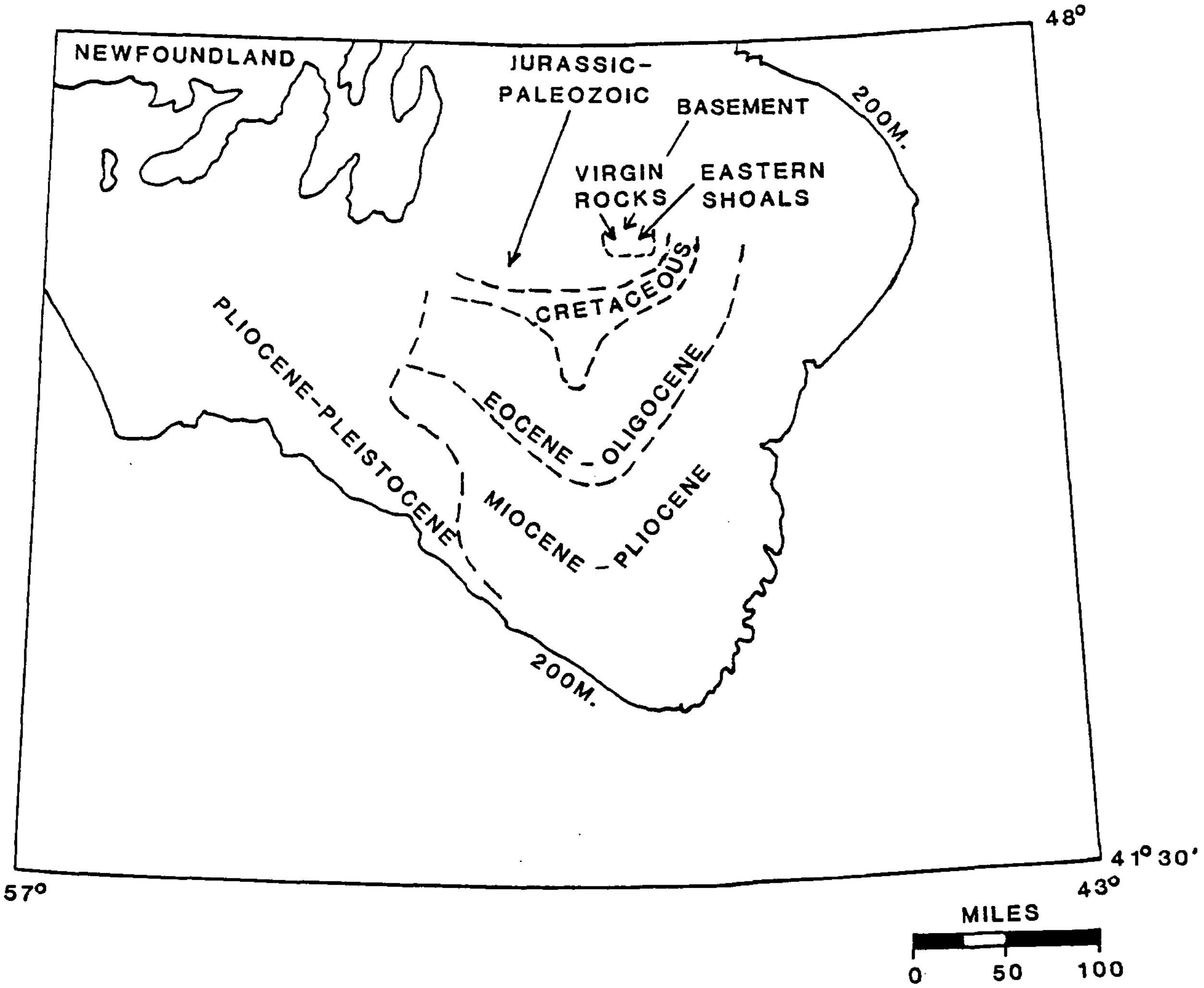


Figure 3. GENERALIZED BEDROCK MAP OF THE GRAND BANKS

Modified after Amoco and Imperial (1973)

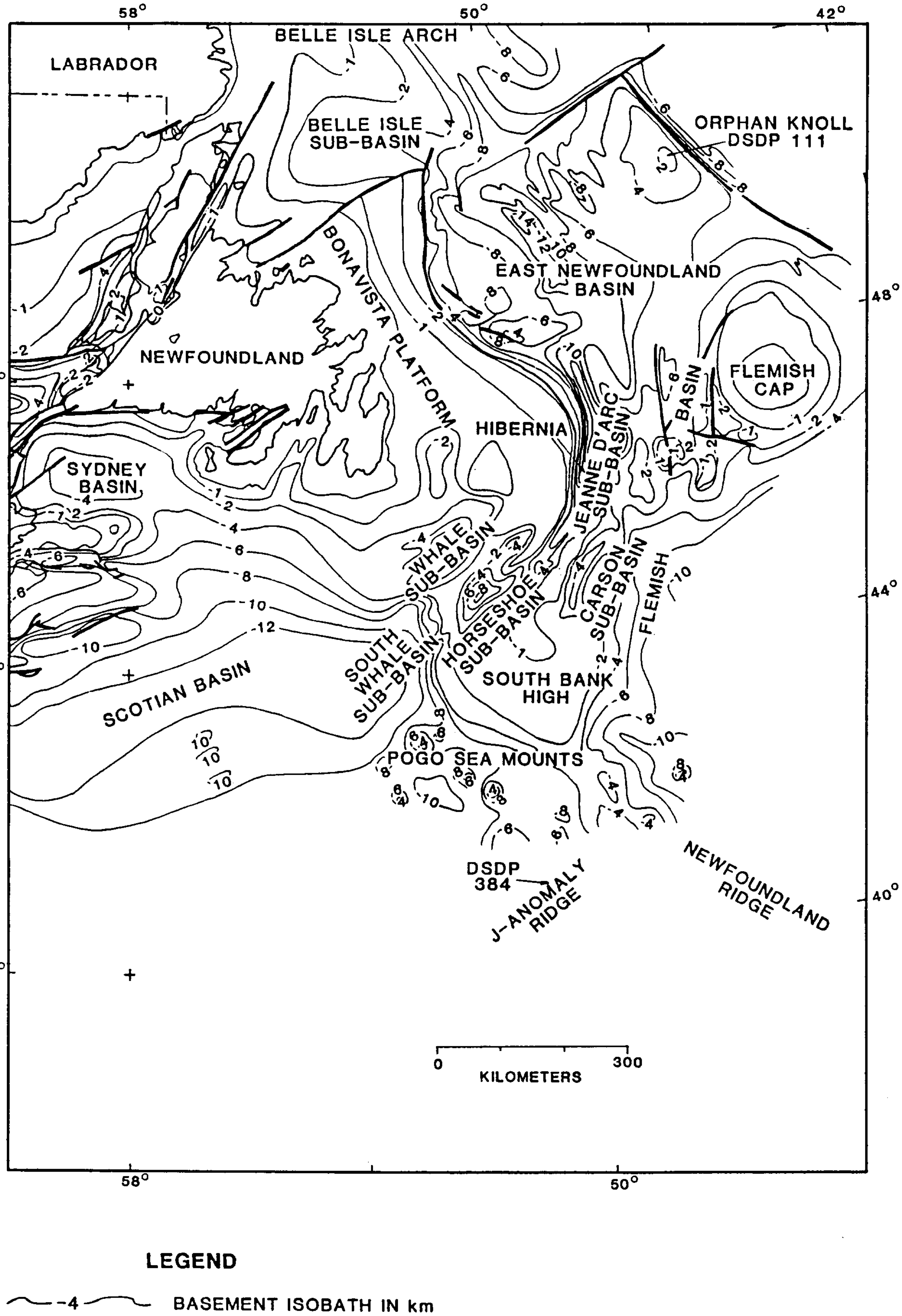
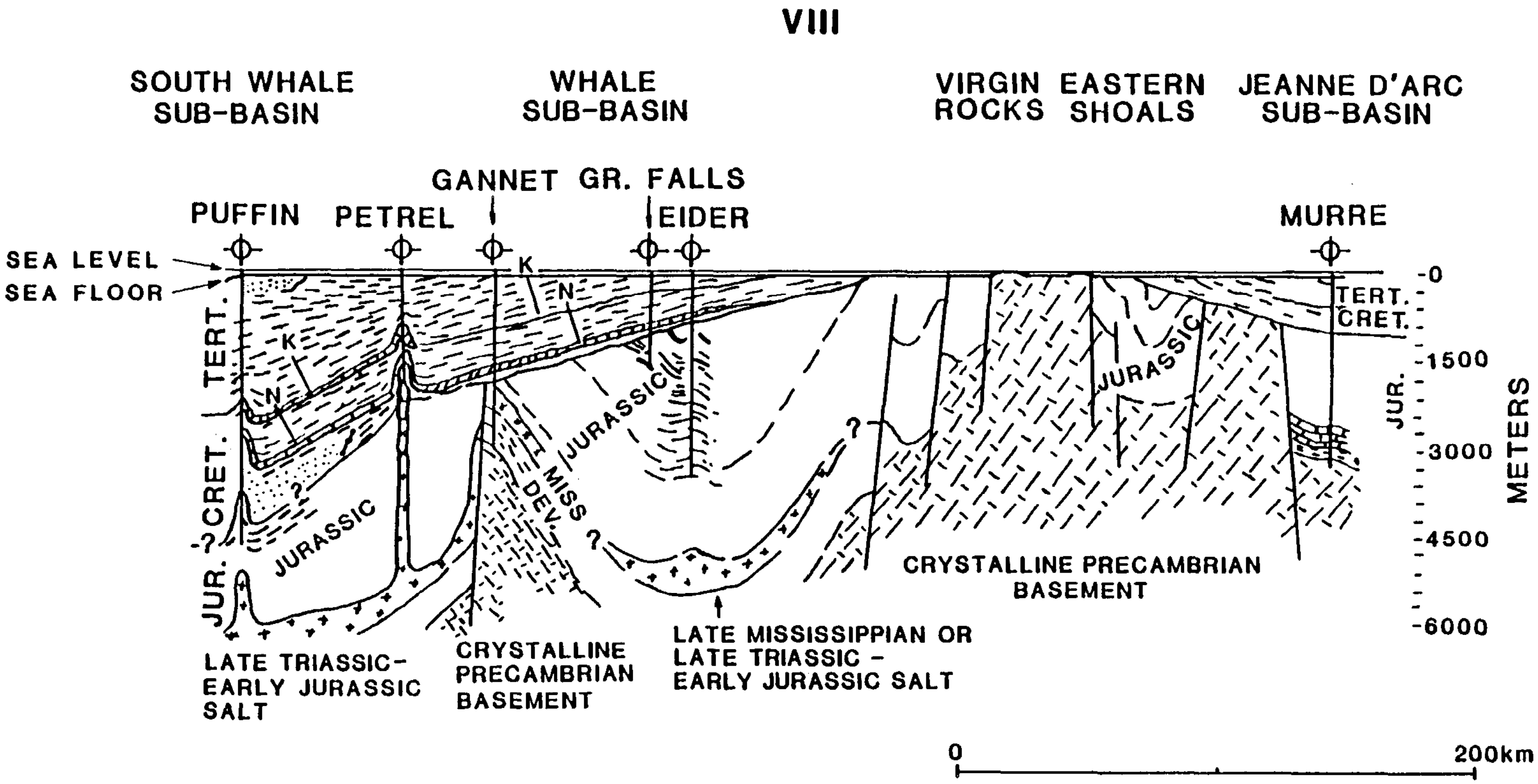


Figure 4. DEPTH TO BASEMENT MAP AND BASIN CONFIGURATION OF OFFSHORE NEWFOUNDLAND

Modified after Jansa and Wade (1975)



LEGEND

K - SEISMIC MARKER - TOP CRETACEOUS
N - PETREL LIMESTONE
AVERAGE WATER DEPTH = 100m

Figure 5. GENERALIZED GEOLOGIC CROSS-SECTION, GRAND BANKS

Modified after Amoco and Imperial (1973)

Late Paleozoic. A thick clastic and evaporitic sequence of mostly Carboniferous age has been recognized. Noteworthy is the massive anhydrite - salt unit (350 m thick) which has been correlated with the Visean Windsor Group of the Maritime Provinces. Some minor coal seams and possible dry gas source are also reported from the top of the section.

A composite stratigraphic section from different wells in the study area is as follows:

- a thick (750 m) clastic sequence with rare coal seams, equivalent with the Namurian - Westphalian Pictou Group of the Maritime Provinces terminated nated the Paleozoic section.

- a red-brown shaly sequence assumed to be a lithostratigraphic equivalent of the Visean - Namurian Conso Group of Nova Scotia.

- an evaporitic series (230 m of massive anhydrite followed by 115 m of massive halite are reported from one well), followed by a shaly red unit, is correlated with the Visean Windsor Group of the Maritime Provinces.

- a red shale, siltstone continental sequence correlated with the Late Devonian - Tournaisian Horton Group, also of the Maritime Provinces, is the lowest unit encountered.

This continental, mostly Carboniferous age succession is followed by a regional, Permian - early to mid Triassic stratigraphic hiatus.

Triassic. The Triassic strata of eastern North America occur in elongated SW-NE trending grabens or half grabens, filled with reddish, fluvial, clastic series and lacustrine sediments, interrupted by basaltic flows. These linear basins have been recognized in the subsurface of the Scotian Shelf and are inferred under the Grand Banks, where some gypsiferous red shales, thought to be equivalent to the Nova Scotian Eurydice Formation have been encountered resting directly above the basement. This gypsiferous shaly formation is overlain unconformably by Early Jurassic strata. This unconformable relationship is possibly restricted to the paleo-basinal margins and may disappear or at least be strongly attenuated in distal basinal sections as exemplified in some Scotian sub-basins. The lack of diagnostic fossils in these non-marine sequences and the lithologic similarities hamper the delineation of the Triassic - Jurassic boundary.

Late Triassic evaporites are known from the Grand Banks ('Osprey Salt') where one well encountered 200 m of almost monomineralic evaporitic lithofacies (halite) following a red shale unit. The true thickness of this salt formation is difficult to assess, considering post-deposition diapirism and the biased nature of the record (most of the wells for which information is available have been drilled purposely atop the flanks of salt diapirs). The lateral extent of the salt is not currently known.

Jurassic. The 'Osprey salt' also encompasses the Early Jurassic. In the best available section, the halite series is sharply overlain by a 350 m thick restricted marine carbonate series dated as Hettangian - Sinemurian.

The next sedimentary interval of Middle Jurassic (Late Pliensbachian to Bathonian) age is variable and poorly understood. It consists of calcareous and silty shales interbedded with argillaceous limestones at the base, followed by a calcarenite unit at the top. This assemblage is reasonably interpreted as characteristic of a low energy, shallow epicontinental sea, spanning the subtidal to open shelf environments. This depositional setting was widespread as documented by the sandstone unit of that age encountered at Orphan Knoll.

The following sedimentary sequence of essentially late Jurassic age (Bathonian to Kimmeridgian) is also variable and consequently not adequately understood. The main lithofacies are organized into three main interrelated depositional environments. The first unit, a Mic Mac Formation equivalent which is slightly older than the type section from the Scotian Shelf, is a typical nearshore, shallow open marine shale sequence, with minor sandstone bodies and infrequent coquina-oolithic limestones and coal seams indicative of a nearshore fluvial environment. It grades basinward into a thick accumulation (800 m) of calcareous shales and argillaceous limestones equivalent to the Verrill Canyon Formation of the Scotian Shelf. Between these two megafacies, there is evidence of an apparently discontinuous carbonate bank complex (bioclastic limestone interbedded with red silty mudstone and very fine grained sandy intercalations, equivalent of the better developed and studied Abenaki Formation of the Scotian Shelf (Eliuk, 1978). In places (best documented along the margin of the Jeanne d'Arc Sub-basin), occur thick (275 m) paralic clastic units containing minor coal seams and oolithic limestones interpreted as coastal environments fed with clastics eroded from a reactivated margin. This can be regarded as an indication of precursor epeirogenic movements of the main Early Cretaceous tectonic phase.

The aggregate thickness of the Jurassic strata reaches 4,000 m.

<u>The Late Jurassic - Early Cretaceous Avalon Unconformity.</u> The continental margin of the northeastern part of the American Craton during the Late Jurassic - Early Cretaceous underwent an epeirogenic period of general uplift and crustal fragmentation. The concomitant, widespread subaerial erosion led to the development of a major unconformity between the truncated pre-Late Jurassic units (including basement horsts) and the post-Early Cretaceous sedimentary cover (Figures 5 and 6). This is referred to as the Avalon Unconformity, and the part of the Grand Banks where it is best developed is named the Avalon Uplift (Figure 7). In this respect the Grand Banks appears as transitional between the quiescent platform of the U.S. Atlantic Coast and Scotian margins to the south and the Labrador Shelf to the north, which underwent major rifting at that time. The large amounts of detrital material which was eroded from the Avalon Uplift accumulated into older depocenters (South Whale Basin) and into the newly active East Newfoundland and Flemish Basins.

The Avalon Uplift (Figure 7), which covers the southern and central part of the Grand Banks overlies the former Jurassic troughs (the Whale, Horseshoe and Carson Sub-basins, referred collectively in the literature as the subunconformity basins) and the intervening basement highs, including the very large South Bank High at the southeastern end of the Grand Banks. The timing of the epeirogenic uplift, block faulting and the resulting erosional and depositional processes is not uniform through the Grand Banks, but it can be postulated that the effects of tectonism reached their climax during the middle to late parts of the Early Cretaceous. Basaltic flows have been encountered in some wells at the level of the unconformity. The unconformity diminishes in magnitude away from the Avalon Uplift and grades

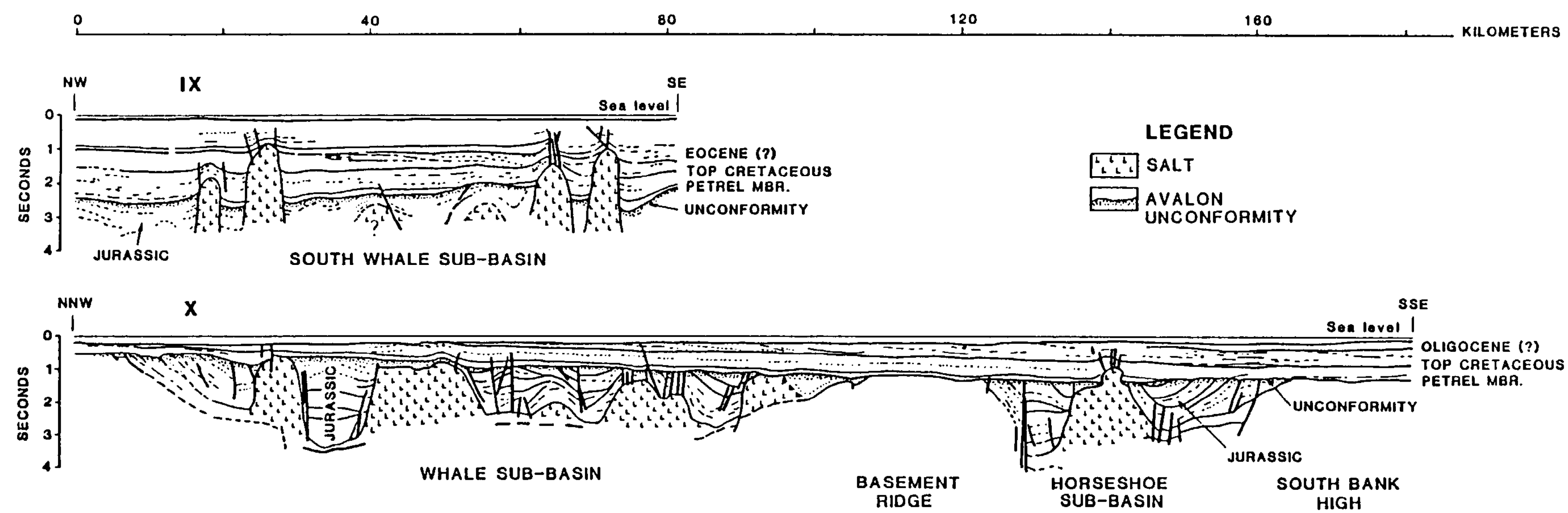


Figure 6. INTERPRETED GENERALIZED SEISMIC PROFILES THROUGH THE SOUTH-CENTRAL GRAND BANKS (AVALON UPLIFT)

Modified after Jansa and Wade (1975)

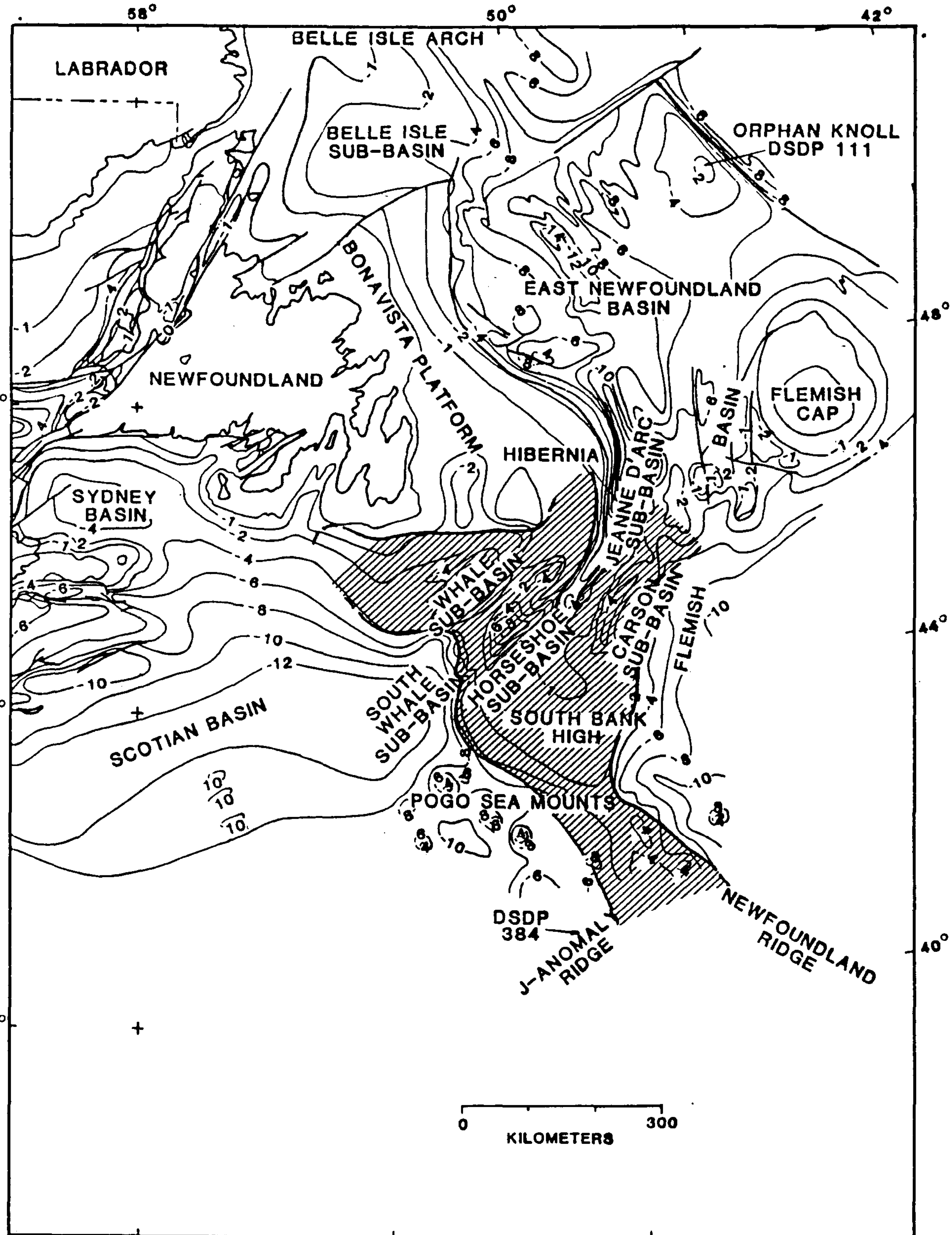


Figure 7. EXTENT OF THE AVALON UPLIFT SOUTH-CENTRAL GRAND BANKS

Modified after Jansa and Wade (1975)

into para-conformable to conformable contacts in the distal parts of the peripheral basins. In this respect, the central part of the Jeanne d'Arc Sub-basin (southern end of the East Newfoundland Basin, (Figure 4) appears to have been unaffected by the epeirogenic event, but its flanks seem to have been tectonically activated at that time, leading to large scale faulting, conducive to the development of structural traps. The Hibernia oil field is a prime example; the hydrocarbons occur in a large roll-over anticline in Upper Jurassic - Lower Cretaceous fluvio-deltaic to marginal marine sandstones (McKenzie, 1981; Procter et al., 1983; Arthur et al., 1982). Some other discoveries have been made along these highly faulted basin margins (Burden et al., 1983) and on subsidiary horsts of the southern Avalon Basin.

Cretaceous to Tertiary. The post-Avalon unconformity sequence, which reaches 4,500 m in thickness and blankets the Avalon Uplift, began earlier and is best developed in the peripheral basinal areas, especially in the newly active Flemish Basin to the east. More drilling data are available from the South Whale Basin, where a 750 m thick sandy sequence which overlapped the southern flank of the Avalon Uplift was deposited. This depositional wedge is dated from the Berriasian - Barremian (Early Cretaceous) in the Scotian Basin where it is fully developed. It is followed in the Whale Basin by Aptian silty dolomitic shales, interpreted as nearshore marine to tidal deposit. first unit to lap over the Avalon Uplift is a thin (25-70 m), nearshore sandstone and shale unit which represents a marine transgressive sequence dated from the late Albian - Cenomanian, time equivalent with the well documented "Cenomanian transgression" of Western Europe and North Africa.

At the same time (i.e. Barremian - Albian to Cenomanian), a discontinuous carbonate bank developed offshore of this fluvio-deltaic complex, fringing the outer continental margin far from the present shelf edge of the Grand Banks.

The Turonian - Coniacian was a time of deposition of a glauconitic, phosphatic carbonate unit, known as the Petrel Limestone. It is a widespread, variable unit very thin at the top of the Avalon Uplift (10 m) and absent from the South Bank High. This is an excellent seismic reflector and marker unit, and is readily interpreted as a marginal marine, shallow to moderately deep shelf sequence.

The next time interval represented by the Santonian - Campanian is characterized by marls and chalks of the Wyandot Formation. This unit is also missing from the Avalon Uplift and is typically interrupted by diastems elsewhere. It can be followed on seismic sections in the East Newfoundland Basin. Coeval reflectors are known from the Flemish Basin. Both previous formations are absent at Orphan Knoll (depositional hiatus).

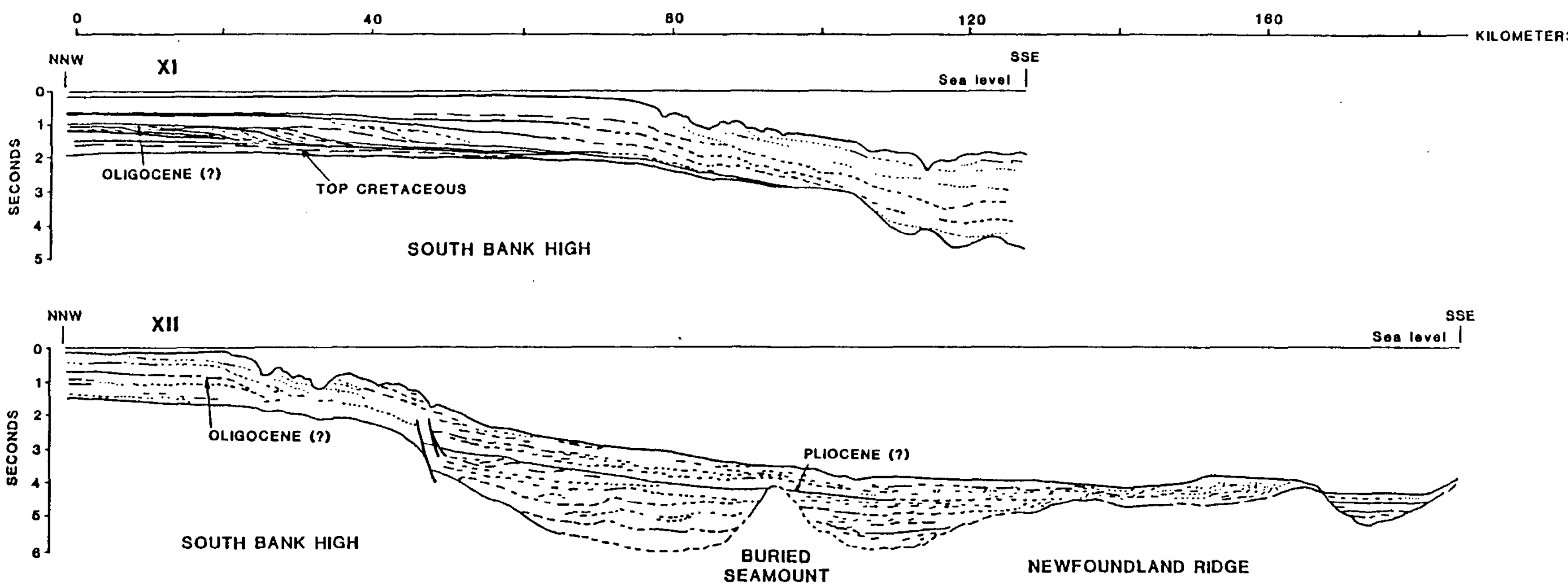
The Maestrichtian - Early Tertiary time sequence is represented by the Banquereau Formation. The Banquereau Formation was first encountered and studied in the Scotian Basin; it is a monotonous mudstone series with subordinate fine-grained glauconitic sand intercalations. The same relative subsidence relationships are observed and a thicker accumulation (2,000 m) is encountered in the South Whale Basin, wedging upon the South Bank High, where it is 600 m thick. The Banquereau Formation is thought to have been deposited in a neritic open shelf environment, which shallowed upward (regressive phase) in Oligocene - Miocene times, when shallow marine glauconitic sandbars were deposited. Widespread hiatuses are frequent, and some are documented to span the entire Santonian to early Eocene sequence. Part of the Paleocene is frequently not represented on the Avalon Uplift but, conversely, a Paleocene chalk facies is recorded from the South Whale Basin. This pattern of nondeposition or post depositional erosion is possibly related to either periods of increased subsidence coupled with little clastic influx, or in changes of sea water circulation pattern on the shelf. Some of the diastems are probably not of regional extent but are local events related to salt diapirism. Also, a pattern of para-conformable hiatuses is documented in the hemipelagic realm at Orphan Knoll.

The general, late Tertiary marine regression started in the late Oligocene. This regressive event, which seems to have affected most of the continental margins on both sides of the northern Atlantic Ocean, can however be correlated in the case of the Grand Banks, with the large influx of clastic material accumulated at that time. The lowering of sea level, which culminated in the latest Pliocene, when the otherwise shallow Grand Banks Shelf was left emergent, coupled with a low subsidence rate and an increase of sediment supply, led to a strong seaward progradation of the shelf margin and the reshaping and steepening of the shelf edge, continental slope region (Figures 8 and 9). Facies change drastically along the new shelf-edge-slope traverse. The increase of sediment diverted from the shelf to the shelf edge and the slope led ultimately to an unstable aggradational wedge. This wedge was characterized by mass resedimentation processes (growth faulting, slumping, turbidity and grain-flow currents), bringing shelf clastics into the bathyal realm and interrupting the autochtonous pelagic carbonate deposition.

Quaternary. The Quaternary history of the Grand Banks of Newfoundland was molded by the same sedimentary processes also active during the late Tertiary, except that detrital material was mainly derived from large continental glacial sheets. The advance and waning of the glaciers, repeated fluctuations of sea level, shelf exposure, and reworking of glacial material during interglacial times, coupled with a very low subsidence rate, led to a very complex depositional history. However the same overall pattern of transient shelf deposition and outbuilding of the shelf edge from the Miocene through the Pliocene sequence is amplified (Grant, 1972).

Glacial drift and stratified proglacial material consisting of gravel and sand beds with localized muddy intervals are variable in thickness and rest on the late Pliocene - early Pleistocene shelf unconformity (Figures 10 and 11). Barring the presence of minor older relict deposits, all this material is related to the sediment influx and reworking processes associated with the last glacial stage (Wisconsin). The northern part of the Grand Banks shows sections locally 200 m thick thought to be related with the margin of a glacial sheet centered on the Avalon Peninsula. South of the Avalon Peninsula, the erosional depression located at the landward edge of the pre-Pleistocene strata has been infilled by approximately 50 m of drift material. The drift cover, averaging 20 m or less in thickness, thins southward. This widespread, thin veneer which makes up the rather uniform sandy bottom of the Grand Banks is inimical for the development of biogenic methane.

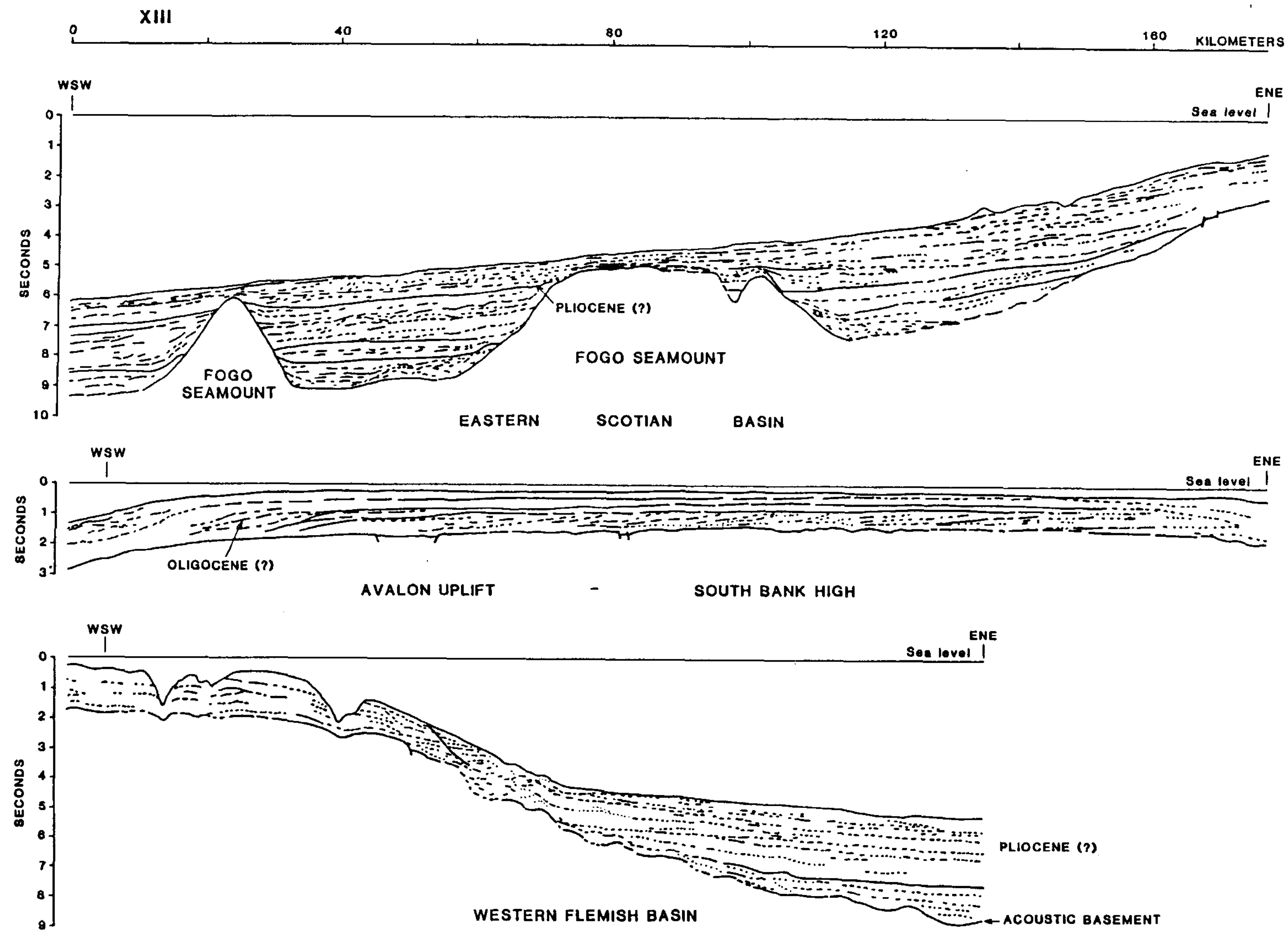
The continuation of the Late Tertiary sedimentary patterns (sediment by-passing of the shelf and accumulation at the shelf edge) dominated the sedimentary history of the Grand Banks through the Pleistocene. It led to a narrow, overall progradational accumulation of sediments, up to 1,500 m in thickness. The continuous foreward building of the shelf edge into deep water, and the subsequent morphological steepening of the slope, record a



NOTE: INTERPRETATION WAS NOT CARRIED THROUGH THE 'ACOUSTIC BASEMENT'

Figure 8. SHALLOW DIAGRAMMATIC SEISMIC PROFILES THROUGH THE SOUTHERN GRAND BANKS (SOUTH BANK HIGH)

Modified after Jansa and Wade (1975)



NOTE: INTERPRETATION WAS NOT CARRIED THROUGH THE 'ACOUSTIC BASEMENT'

Figure 9 SHALLOW DIAGRAMMATIC SEISMIC PROFILE THROUGH THE SOUTHERN GRAND BANKS (SOUTH BANK HIGH)

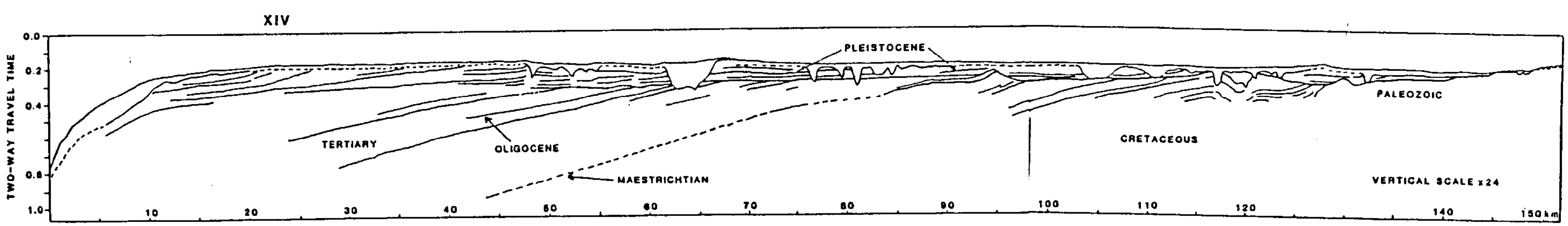


Figure 10. DIAGRAMMATIC SHALLOW SEISMIC PROFILE FROM THE GRAND BANKS
Modified after King and McLean (1975)

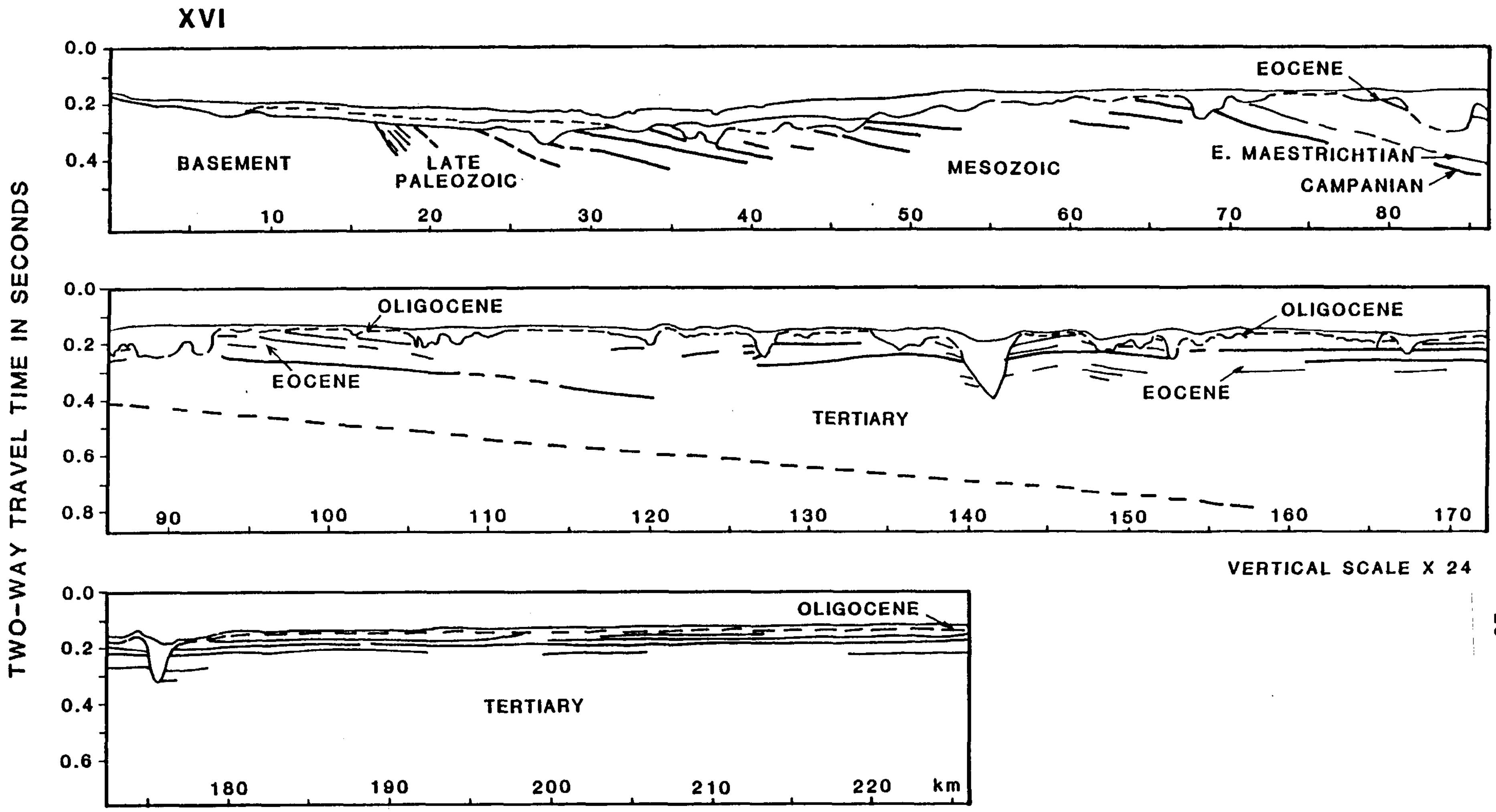


Figure 11. DIAGRAMMATIC SHALLOW SEISMIC PROFILE FROM THE GRAND BANKS

Modified after King and McLean (1975)

more complete depositional history. The upper slope was and still is dominated by gravity induced resedimentation processes (Heezen and Drake, 1964). Submarine canyon erosion, debris flow and turbidity currents, slumping and other mass movement mechanisms led to a major material transfer from the shelf edge to the base of the slope and to the abyssal plains.

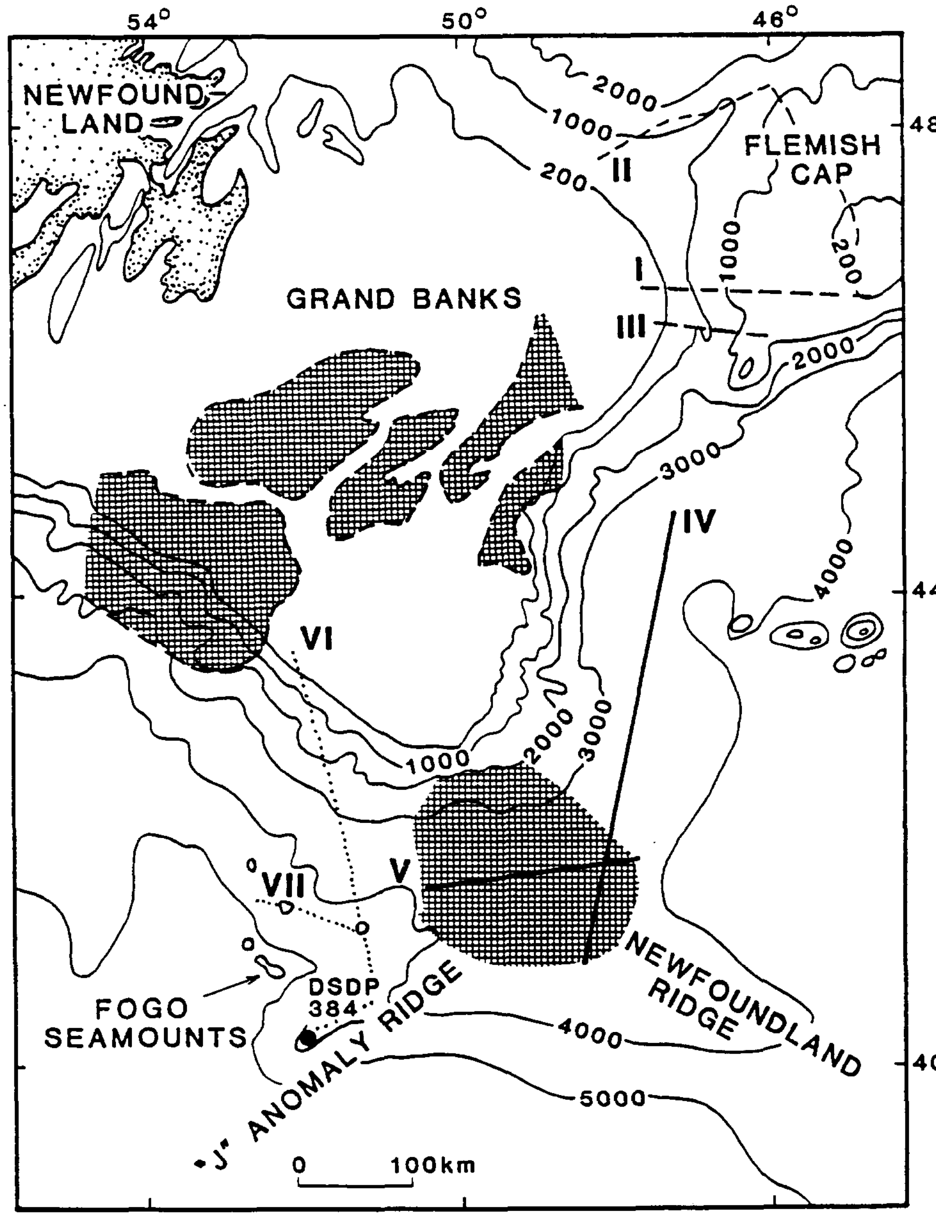
Flemish Cap is a shallow (200 m isobath) plateau located 650 km east of the Avalon Peninsula and more than 150 km seaward from the eastern edge of the Grand Banks shelf, beyond a deep strait (>1,000 m water depth) known as Flemish Pass (Figure 12). Its top has been drilled (Pelletier, 1971), revealing a granodiorite dated at 590 ± 20 m.y. Quartzite blocks have also been dredged from the top of the plateau. This basement complex is overlapped westward by a thick sedimentary sequence of the Cretaceous - Tertiary Flemish Basin (Grant, 1973; Jansa and Wade, 1975; Figures 13 and 14). Early Cretaceous platform limestones have been dredged from the south flank of Flemish Cap at more than 1,500 m water depth (Sen Gupta and Grant, 1971) and also from an unspecified Newfoundland seamount (Sullivan and Keen, pers. commun. in Gradstein et al., 1977).

Orphan Knoll is an important geological feature because it represents the first documented occurrence of a continental block at bathyal depths, previously considered the domain of oceanic crust. It is also the location of a deep drill hole equidistant between two possible BSRs. The Flemish Cap plateau lies under shallow water (<200 m) like the Grand Banks and consequently, the occurrence of a variety of continental crust lithologies was not very surprising. However, the discovery by the Deep Sea Drilling Project (DSDP) at Site 111 of another continental block located far to the northeast of Newfoundland at bathyal depths was unexpected. This feature was named the Orphan Knoll by the Canadian Hydrographic Service in 1970.

The Orphan Knoll is located some 550 km northeast of the coastline of Newfoundland. It is a 100 km diameter mount or plateau whose top lies at 1,800 m water depth. The knoll rises 1,000 m to 2,400 m above the surrounding sea floor.

DSDP Site 111, in conjunction with dredged material, proved conclusively that Orphan Knoll is a foundered fragment of the North American craton lying at abyssal depths. The Site 111 hole (preliminary results in Laughton et al., 1970; initial reports in Laughton et al., 1972) bottomed in an alluvial, marginal marine, Middle Jurassic (Bajocian) sandstone beneath a platform carbonate sequence of Albian - Cenomanian age. Platform type Devonian limestones have been dredged from the top of the Orphan Knoll plateau (Ruffman and van Hinte, 1973) and some dredged sediments of Silurian age have also been collected (Legault, 1982). Shallow bathymetric and seismic profiles (Laughton et al., 1972; Ruffman and Van Hinte, 1973) have shown prominent sea floor ridges. A recent investigation by Parsons et al. (1984) regards the ridges as exhumed Devonian pinnacle reefs.

Seismic profiles have shown the continuity of sedimentary reflectors from the Grand Banks to Orphan Knoll (East Newfoundland Sub-basin; Figure 13). Detailed bathymetric, magnetic and gravity surveys have confirmed that the entire intermediate depth area of the wide northeastern Newfoundland shelf, inshore of Orphan Knoll and Flemish Cap is continental in character (Haworth, 1977), thus invalidating previous reconstructions. In particular, geophysical anomalies have been shown to be more readily interpretable as continuations of onshore structural trends than related to oceanic crustal features.



LEGEND

CONTOURS IN METERS

CROSS-HATCHED AREAS INDICATE THE EXTENT OF THE SUB-UNCONFORMITY BASINS OF THE GRAND BANKS

——— SEISMIC PROFILE LOCATION (after Grant, 1977)

·········· SEISMIC PROFILE LOCATION (after Uchupi and Austin, 1979)

---- SHALLOW SEISMIC PROFILE LOCATION (after Grant, 1972)

Figure 12. BATHYMETRIC MAP OF THE GRAND BANKS NEWFOUNDLAND - J-ANOMALY RIDGES

Modified after Grant (1977)

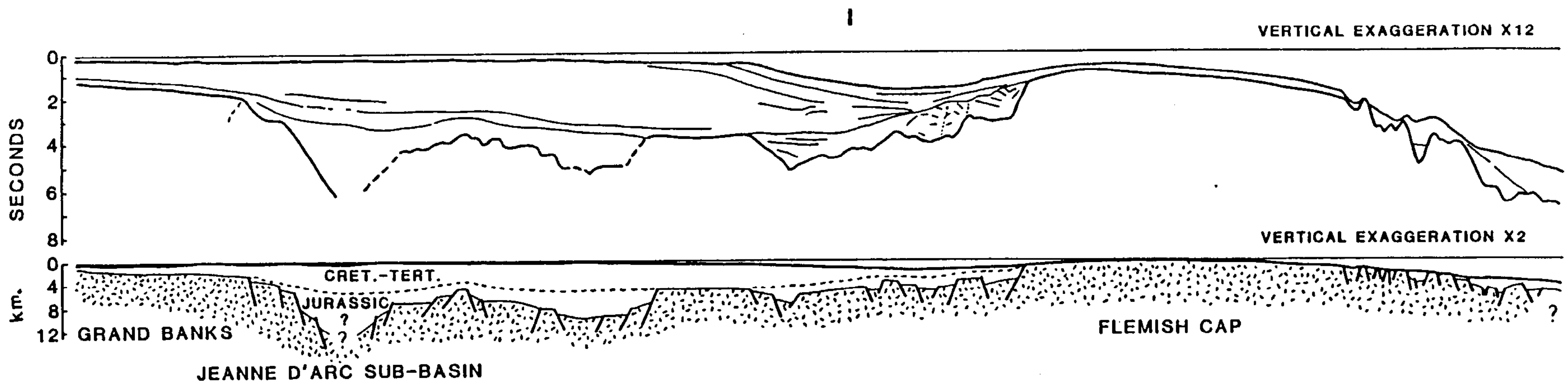


Figure 13. DIAGRAMMATIC SEISMIC PROFILE AND GEOLOGIC INTERPRETATION THROUGH FLEMISH CAP - JEANNE D'ARC SUB-BASIN - NORTHERN GRAND BANKS

Modified after Grant (1975)

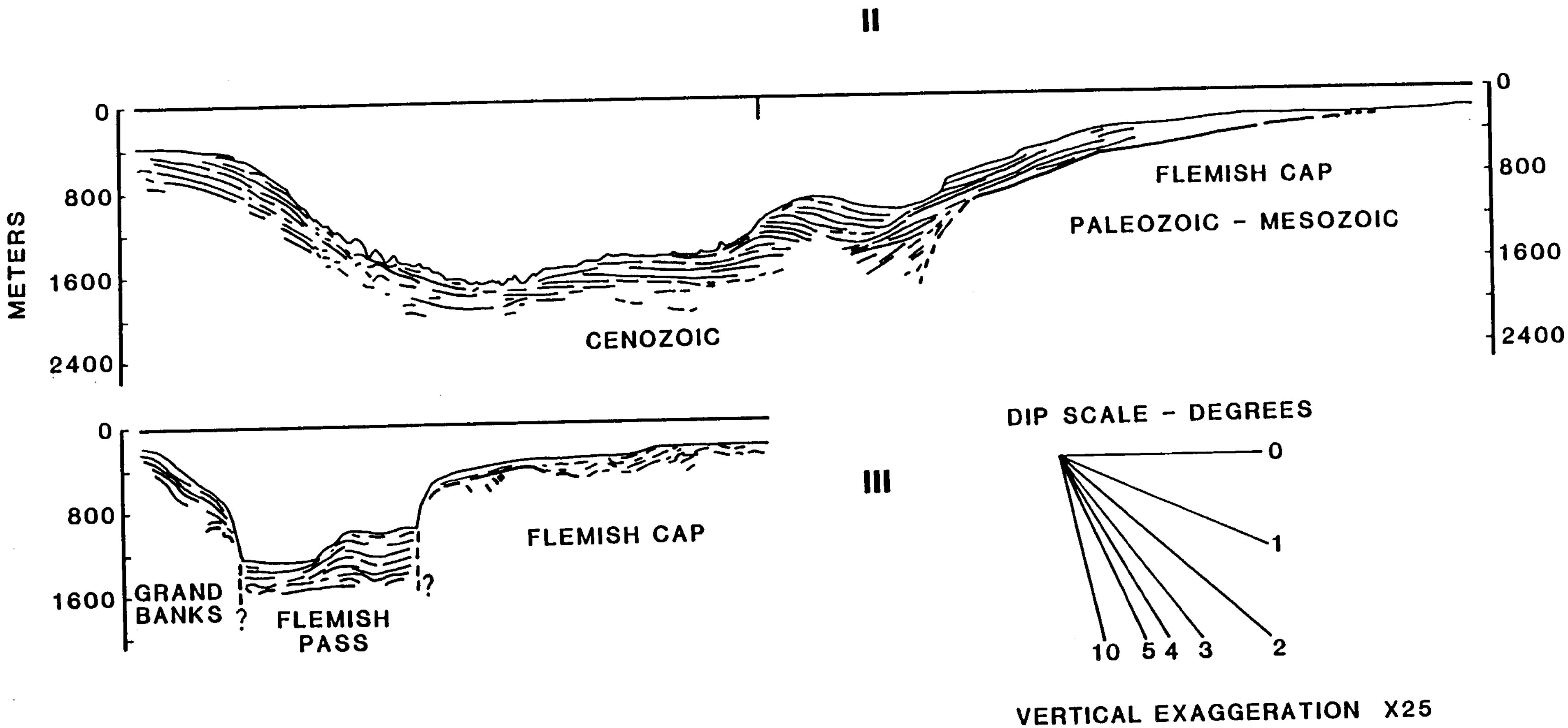


Figure 14. DIAGRAMMATIC SHALLOW SEISMIC PROFILES THROUGH FLEMISH PASS

Modified after Grant (1972)

The timing of the foundering of the continental margin at Orphan Knoll is constrained by the sedimentary sequence unveiled by the DSDP Site 111 (Figure 15). The Cretaceous shallow water limestones are abruptly terminated by a phosphorus-manganese nodule hardground representing a prolonged, nondeposition episode in fairly deep water, overlain by a late Maestrichtian coccolithic, calcareous, partly lithified ooze. The quiet bathyal environment continued with hiatuses (latest Maestrichtian to early Eocene, late Eocene to late Miocene) up to the late Pliocene. The influx of ice-rafted clastics heralded the onset of the Pleistocene glaciation. The stratigraphic record has been interpreted (Laughton et al., 1972; Umpleby, 1973; Ruffman and van Hinte, 1973) in terms of rapid subsidence outpacing sedimentation during the latest Cretaceous - Paleocene and subsequent stabilization of the plateau at bathyal depths (Figure 16).

The beginning of increased subsidence and concomitant outpacing of the sediment input could be as recent as Late Cretaceous. Supportive evidence provided by Laughton et al. (1972) indicate that a phosphorus and manganese hardground was developed on Cretaceous carbonates and that the overlying late Maestrichtian coccolithic chalk were hemipelagic sediments deposited at great water depths.

Newfoundland Ridge. In the late 1970s, attention was focused on the deep-water ridge which extends 900 km seaward from the southeastern edge of the Grand Banks, known as the Newfoundland Ridge (Grant, 1977, 1979; Gradstein et al., 1978; Figure 12). This ridge lies in 3000 m to 4000 m of water and was previously assumed to be an oceanic feature located along a major oceanic transcurrent fault (Auzende et al., 1970; Le Pichon and Fox, 1971; Watson and Johnson, 1970; Keen et al., 1977). In two provocative papers, Grant (1977, 1979) showed convincingly that the Newfoundland Ridge is a foundered fragment of the continental margin. The evidence for this interpretation is based on an integrated interpretation of deep seismic sections. The continuity of the unconformity of the southern Grand Banks, which corresponds to a major angular unconformity, has been traced in deep water, across the western part of the Newfoundland Ridge (Figure 17). The same seismic pattern of tilted deep reflections truncated by a major regional reflector itself overlain by almost undisturbed strata has also been documented (Figure 17).

These seismic reflection data imply the presence of tilted sub-basins unconformably overlain by an undisturbed, gently sloping sedimentary sequence. The pre-unconformity sedimentary rocks thicknesses are similar to those documented from the Grand Banks (6,000 - 8,000 m). The same basic age relationship is also implied, and the unconformity seismic event can be correlated with the Early Cretaceous Avalon unconformity of the Grand Banks. The presence of sub-unconformity basins also raises questions regarding their sialic basement. Such an interpretation has been questioned by Keen et al. (1977) and Sullivan and Keen (1978) who prefer an oceanic origin for the Newfound- land Basin.

J - Anomaly Ridge is a morphological feature which derives its name from its position above a major magnetic sea floor spreading isochron of the northern Atlantic Ocean. It appears as a spur, oriented NE-SW, normal to the Newfoundland Ridge (Figure 17). The J - Anomaly Ridge was interpreted to be an oceanic crust feature (Auzende et al., 1970; Le Pichon et al., 1971).

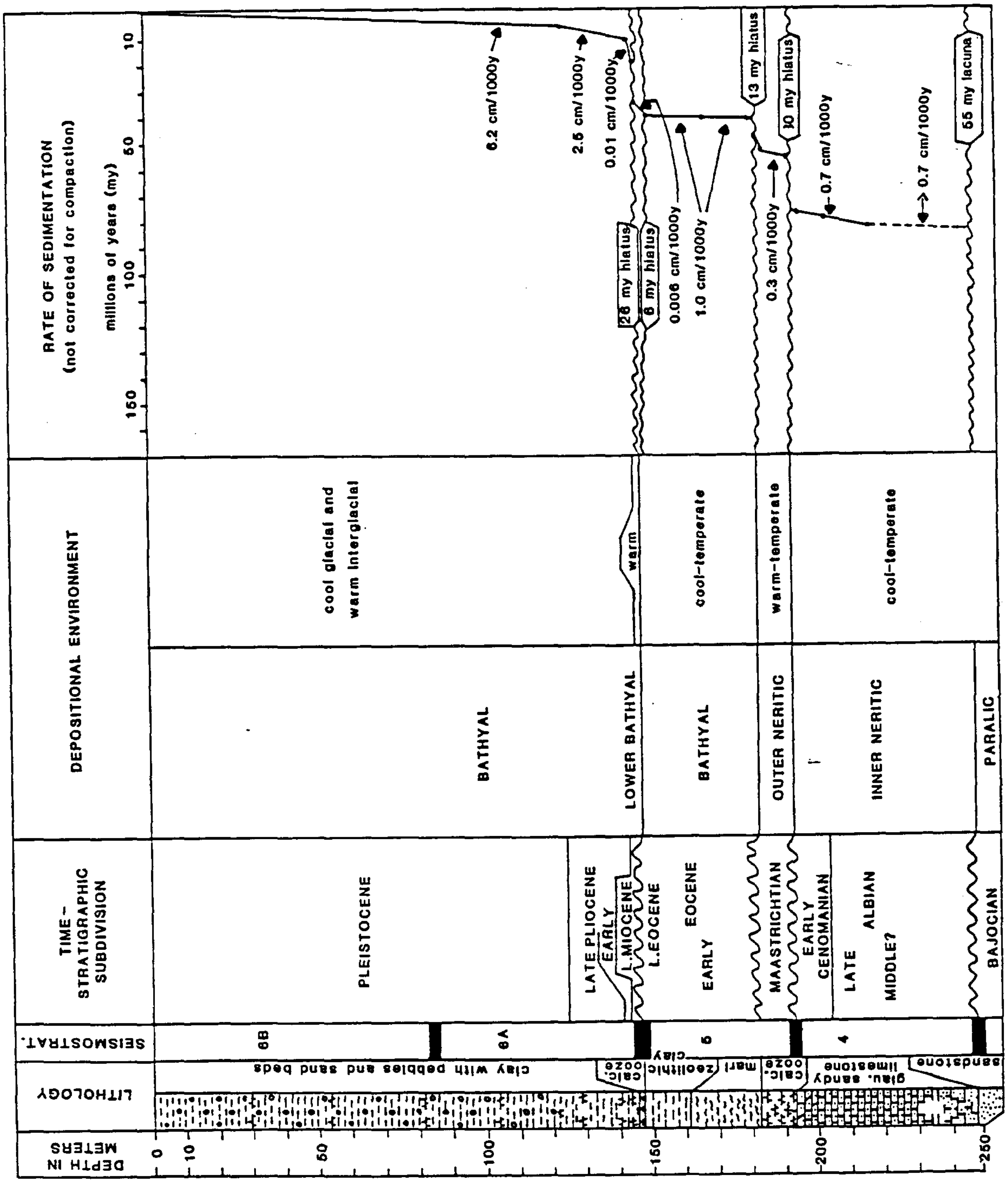


Figure 15. STRATIGRAPHY - DEPOSITIONAL ENVIRONMENT AND SEDIMENTATION RATE FOR ORPHAN KNOLL (DSDP SITE 111)

Modified after Laughton et al. (1972)

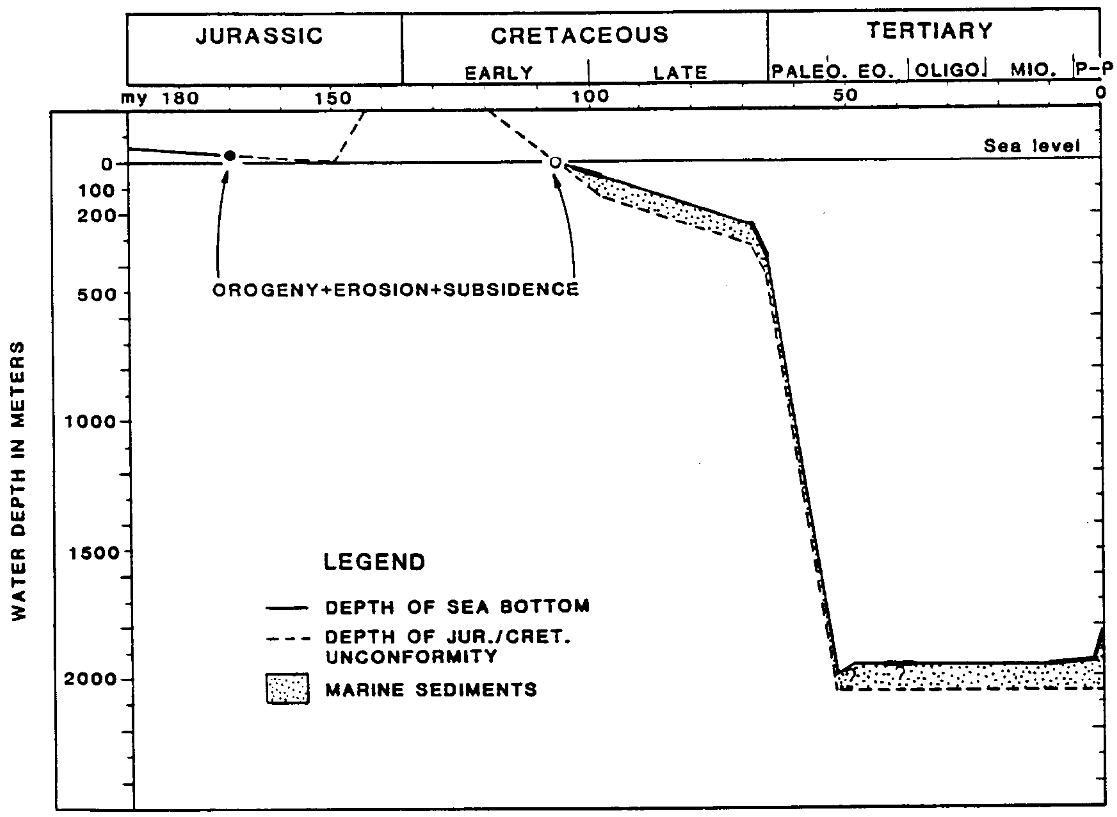
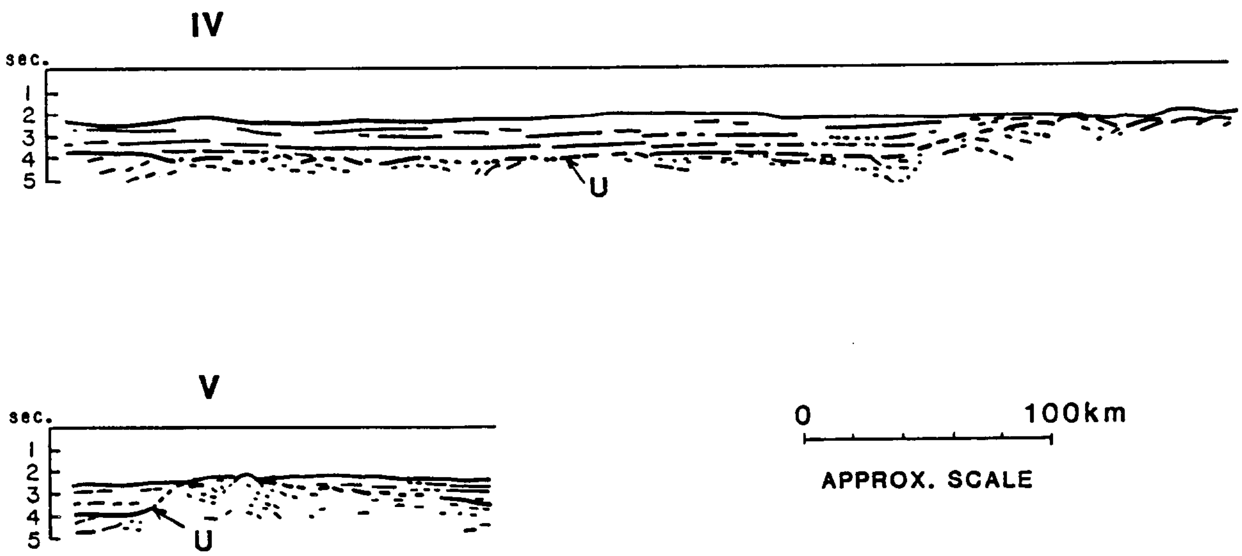


Figure 16. SUBSIDENCE HISTORY OF ORPHAN KNOLL (DSDP SITE 111)

Modified after Laughton et al. (1972)



LEGEND

POST UNCONFORMITY REFLECTORS

PRE UNCONFORMITY REFLECTORS

U UNCONFORMITY

Figure 17. DIAGRAMMATIC SEISMIC PROFILES THROUGH THE NEWFOUNDLAND RIDGE

Modified after Grant (1977)

Gradstein et al. (1977) proposed that the J - Anomaly Ridge shared the same basic geological framework with the Newfoundland Ridge and is also a continental block sunken to 3,000 to 5,000 m. The evidence is not based on deep seismic profiles, which are not available, but from DSDP Site 384 (Tucholke et al., 1975, 1979; Figure 18). This hole was drilled in 3,920 m of water, penetrated 330 m of sediment and bottomed in a basaltic flow showing signs of subaerial alteration. The basalt is overlain by Barremian - Aptian/Albian shallow water, shelf, bioclastic limestones, interpreted as a back reef facies.

This Lower Cretaceous carbonate sequence is also documented from dredge samples recovered from the J - Anomaly Ridge. Coeval limestones are known from the southern Grand Banks (Jansa and Wade, 1975; Jansa, 1981) and the Scotian Shelf (Eliuk, 1978) and are seismically inferred from the tops of some of the Fogo Seamounts (Uchupi and Austin, 1979). The basaltic flow, in which the hole bottomed, is not typical oceanic basalt (Rabinowitz et al., 1978; Tucholke et al., 1979), but a stratigraphic equivalent of the syn-unconformity, Early Cretaceous basalt flows, known at that level from the Grand Banks, and also from the Labrador Shelf (McWhae and Michel, 1975). The fact that the basalt shows a vesicular pattern and a type of alteration typical of subaerial erosion (Tucholke et al., 1979) strongly supports this interpretation.

The existence of the Early Cretaceous Avalon unconformity is indirectly confirmed by and can be correlated with similar seismically defined occurrences in the western part of the Newfoundland Ridge. One seismic line (Gradstein et al., 1977) extending from the southern Grand Banks to the area of junction, between the western Newfoundland Ridge and the northeastern termination of the J - Anomaly Ridge (Figure 17), clearly shows the trace of the unconformity. It can also be extrapolated across some of the Fogo Seamounts (Uchupi and Austin, 1979), where seismically defined Lower Cretaceous reef limestones rest on the acoustic basement (Figure 19). These seamounts are aligned en echelon, parallel to the shelf edge and are thought to be localized along a major fracture zone bordering the southern Grand Banks.

The inferred continental nature of the crust beneath the J - Anomaly Ridge, has not found general acceptance and has been rejected by Rabinowitz et al. (1978), Tucholke et al. (1979), Rabinowitz et al. (1979), Uchupi and Austin (1979). The lack of deep seismic resolution has been generally interpreted as a lack of reflectors within oceanic crust material.

The subsidence pattern inferred from DSDP Site 384 is strikingly similar to DSDP Site 111 at Orphan Knoll, located more than 1,000 km to the north-northeast of the J - Anomaly Ridge (Figure 20). The bioclastic, Cretaceous platform carbonate sequence is older (late Barremian to Aptian versus Albian - Cenomanian) at Orphan Knoll, and displays at its top, fabrics characteristic of subaerial exposure. It is abruptly overlain by Coniacian - Santonian, thin nannofossil ooze which gives way upwards, after a depositional hiatus, to late Maestrichtian - early Paleocene chalks. The chalks grade upwards, after another hiatus, to a chert and porcellanite horizon of early Eocene age. and nannofossil oozes of middle Eocene age. The top section was not cored. Site 384 apparently underwent very rapid subsidence, in excess of that caused by sediment influx, during the Late Cretaceous and was subsequently stabilized at great depth.

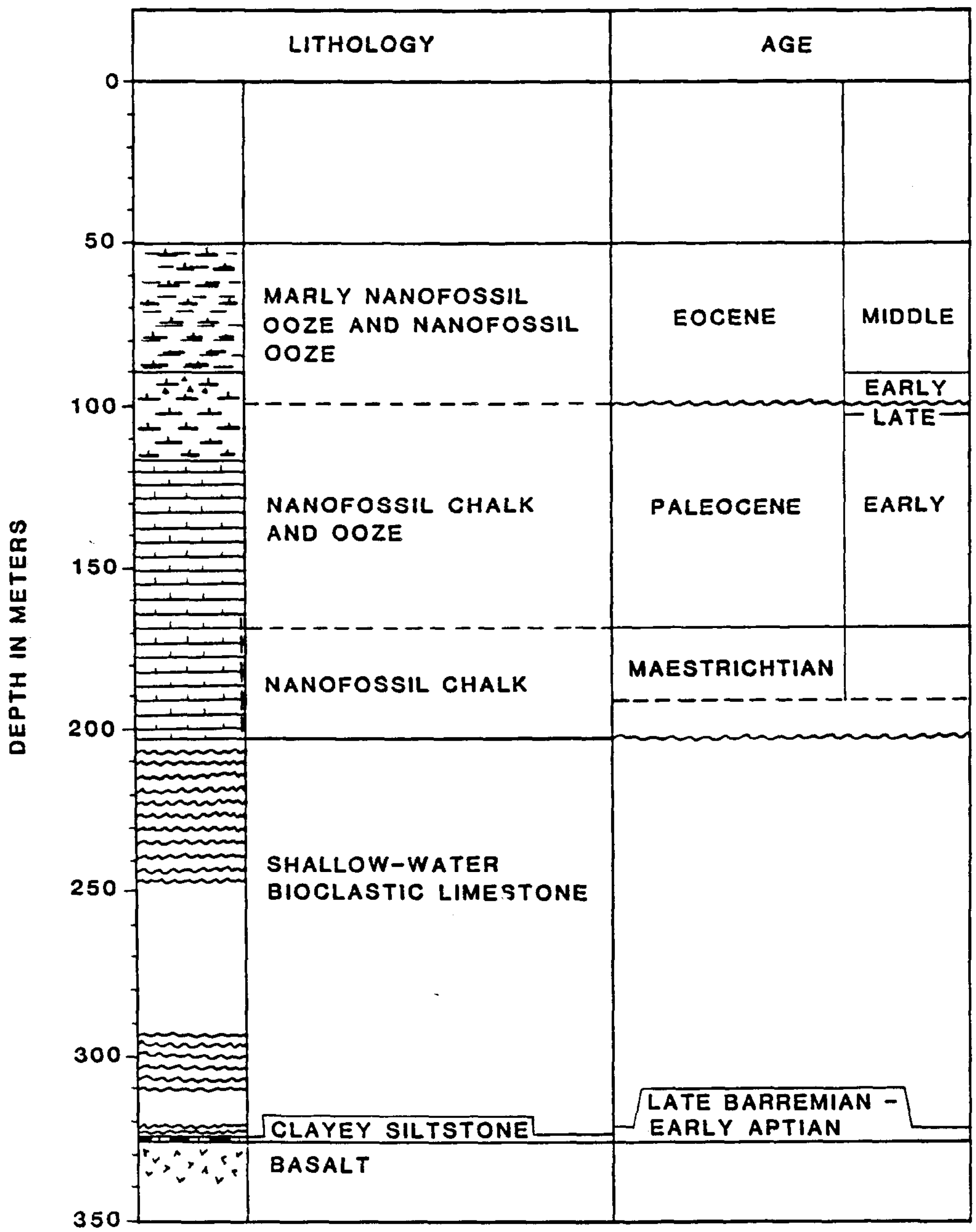
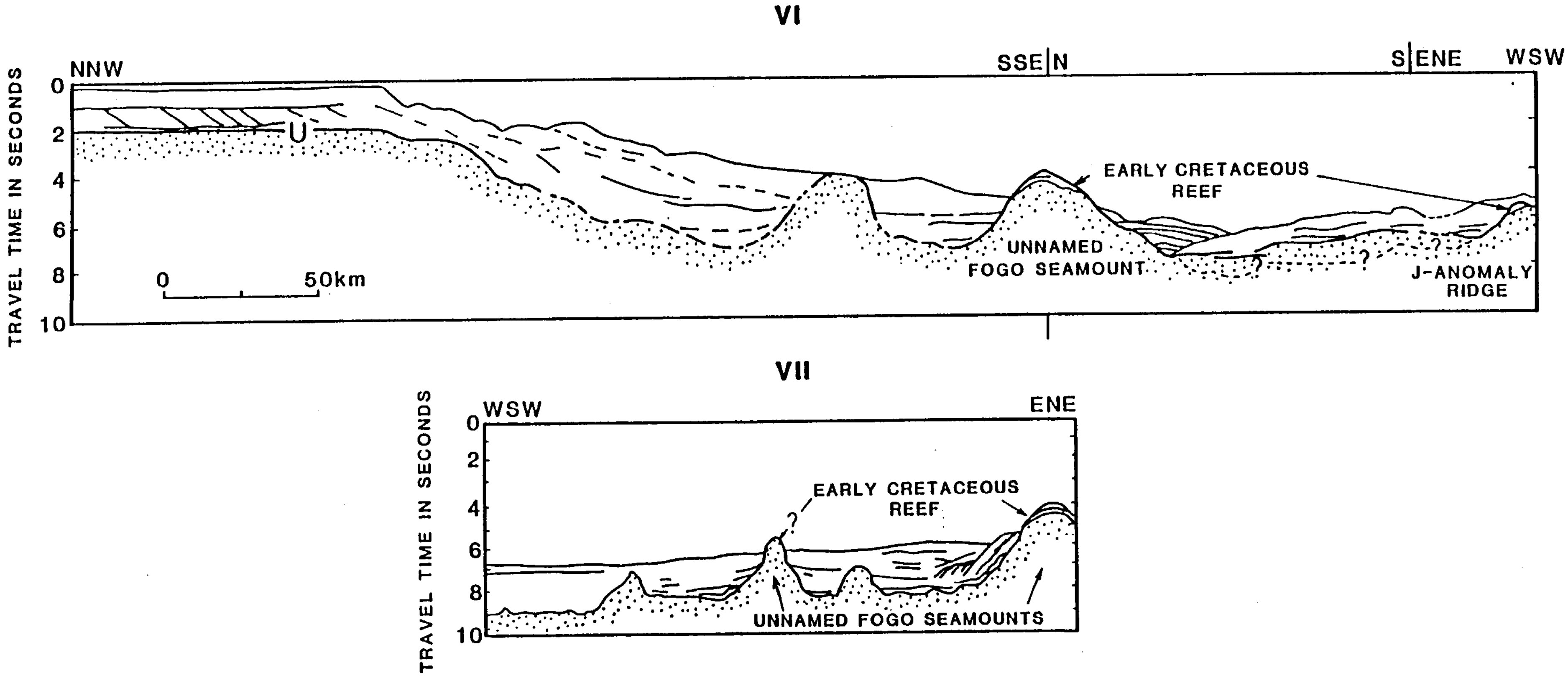


Figure 18. STRATIGRAPHIC COLUMN FOR DSDP SITE 384 (J-ANOMALY RIDGE)

Modified after Tucholke et al. (1979)



NOTE: PRE-"ACOUSTIC" BASEMENT AND/OR PRE-AVALON UNCONFORMITY REFLECTORS (STIPLED AREA) NOT DIFFERENTIATED IN THIS INTERPRETATION.

Figure 19. DIAGRAMMATIC SEISMIC PROFILES FROM THE SOUTHERN FLANK OF THE GRAND BANKS AND J-ANOMALY RIDGE

Modified after Uchupi and Austin (1979)

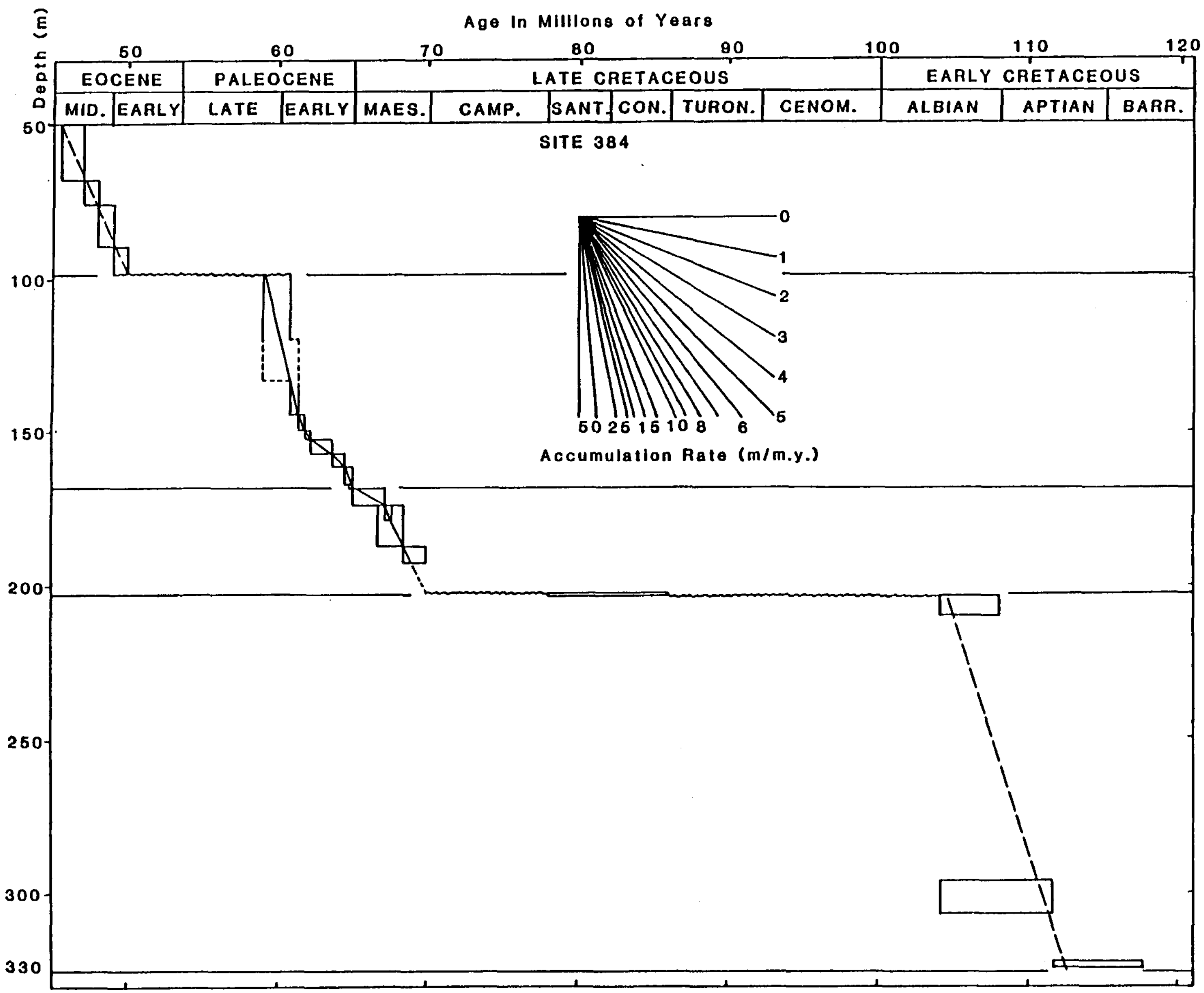


Figure 20. RATE OF SEDIMENT ACCUMULATION CHART FOR DSDP SITE 384 (J-ANOMALY RIDGE)

Modified after Tucholke et al. (1979)

Petroleum Geology

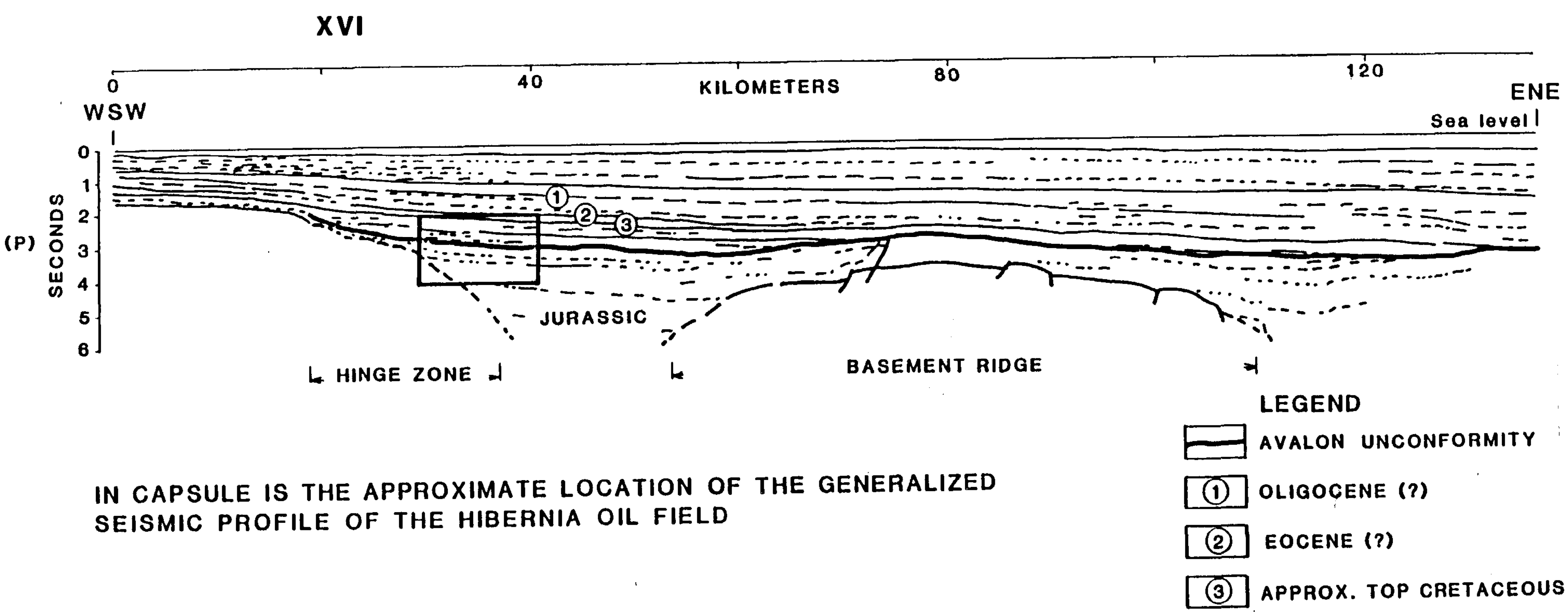
The first phase of oil exploration in the Newfoundland Continental Margin was concentrated in the southern half of the Grand Banks, and although many oil and gas shows were encountered, no economical fields were found. The exploration effort was then diverted to the northeastern part of the Grand Banks (Jeanne d'Arc Sub-basin). The first well was drilled in 1971, but it was not until 1979 that the giant Hibernia oil field was discovered by a group led by Mobil Co. (Procter et al., 1983). This field is located 315 km east - northeast of the Avalon Peninsula, in less than 100 m of water. It produces from several horizons at 2,200 to 2,400 m sub-bottom depth. The reservoirs are Upper Jurassic - Lower Cretaceous, fluvio-deltaic to marginal marine sandstones. The field which is reported to contain over 1 billion barrels of oil and 2 trillion cubic feet of gas and is tentatively expected to be put in production at the beginning of the next decade (Oil and Gas Journal, 1985). The Jeanne d'Arc Sub-basin offers an outstanding potential and other discoveries of smaller magnitude have been reported from other structures of this basin (Arthur et al., 1982; Burden et al., 1983).

The tectonic pattern of the Grand Banks of Newfoundland has been dominated by deep seated basement block faulting, which reached its acme during the Early Cretaceous. This extensional tectonic regime led to the differentiation of well individualized troughs separated by intervening horst features (sub-basins and highs) and caused the post-tectonic development of an angular unconformity of regional extent (Figure 21). The block faulting extensional pattern is also well displayed at a local scale and in a different tectonic mode.

Sediment draping over up-faulted basement highs, tilted fault blocks "roll-over" anticlines associated with extensional faults, and salt diapir piercements structures have been the prime exploration targets (Arthur et al., 1981; Burden et al., 1983; McKenzie, 1981; Procter et al., 1983). The best documented structure is the Hibernia oil and gas field. Briefly the Hibernia oil and gas field, which is located along the western flank of the narrow Jeanne d'Arc Sub-basin is interpreted as a very large, faulted roll-over anticline, developed downdip from a major listric growth fault (Figures 22 and 23). The domal structure is by secondary listric growth faults and associated antithetic faults. Typically, in the Hibernia oil and gas field, the Early Cretaceous reservoirs (fluvio-deltaic to marginal marine sandstones) show an increase in thickness toward the trace of the main fault, indicating its syn-sedimentary nature. The Hibernia structure documents the Late Jurassic - Early Cretaceous syn-sedimentary, extensional tectonic activity, which affected the Grand Banks. The Avalon Unconformity, which becomes intraformational within the basinal area, is well developed along the western flank of the Jeanne d'Arc Sub-basin and is precisely dated as pre-Aptian. Minor offset by faulting documents the continuation and final waning of structural deformation which occured during the latest Early Cretaceous. Separate nearby structures, also located along the basin eastern and western flanks have been seismically delineated and successfully tested. This structural pattern extends northward into the deep Newfoundland Basin.

The salient geologic feature of the Grand Banks of Newfoundland is the Cretaceous epeirogenic event that caused the Avalon Unconformity.

Together with the East Newfoundland Basin and the Labrador Shelf, this is the only part of the eastern North American continental margin where



IN CAPSULE IS THE APPROXIMATE LOCATION OF THE GENERALIZED SEISMIC PROFILE OF THE HIBERNIA OIL FIELD

Figure 21. SEISMIC PROFILE THROUGH THE NORTHERN GRAND BANKS-JEANNE D'ARC SUB-BASIN

Modified after Jansa and Wade (1975)

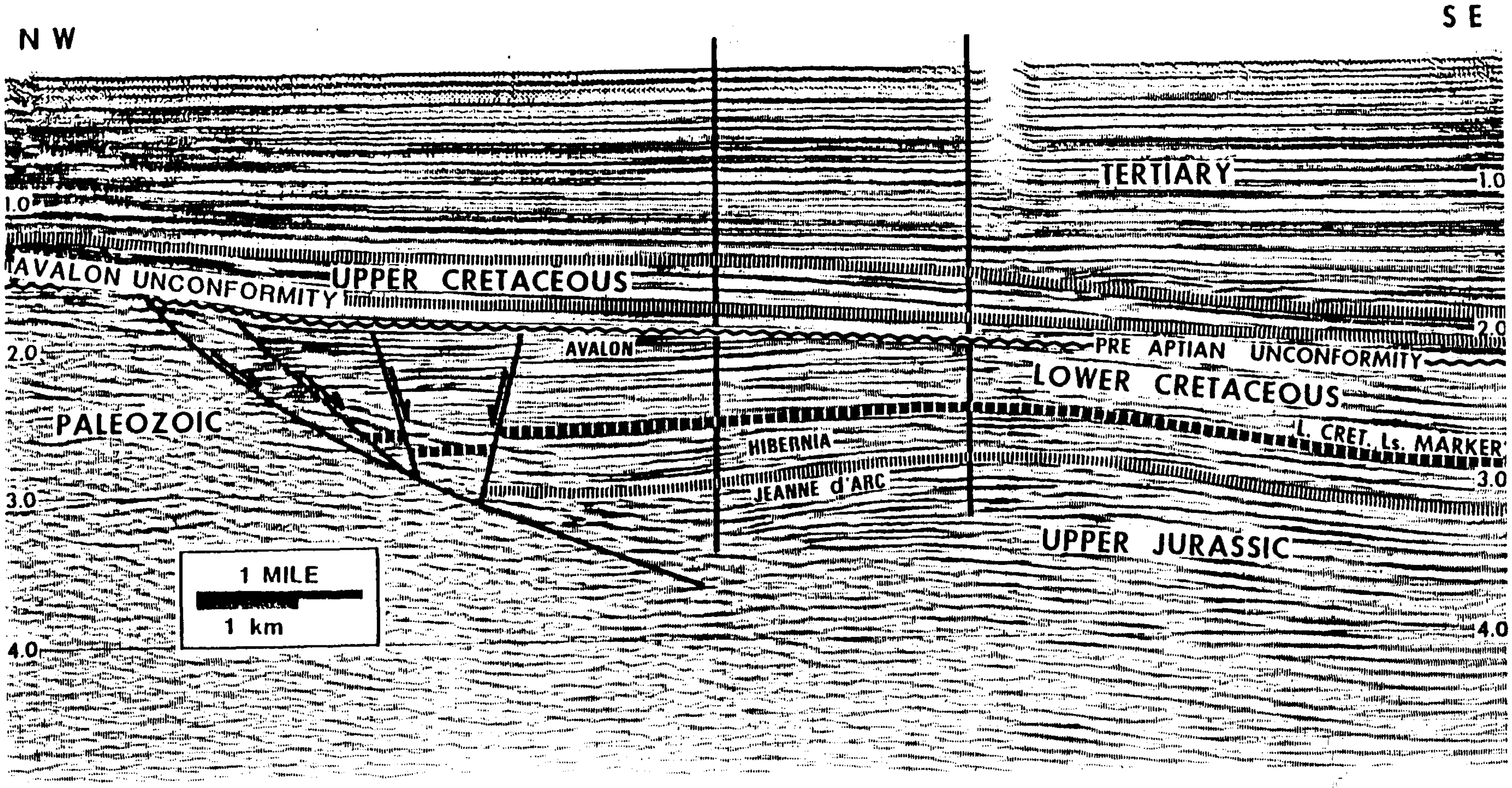


Figure 22. SEISMIC SECTION THROUGH THE HIBERNIA OIL AND GAS FIELD NORTHERN GRAND BANKS

After Arthur et al. (1982)

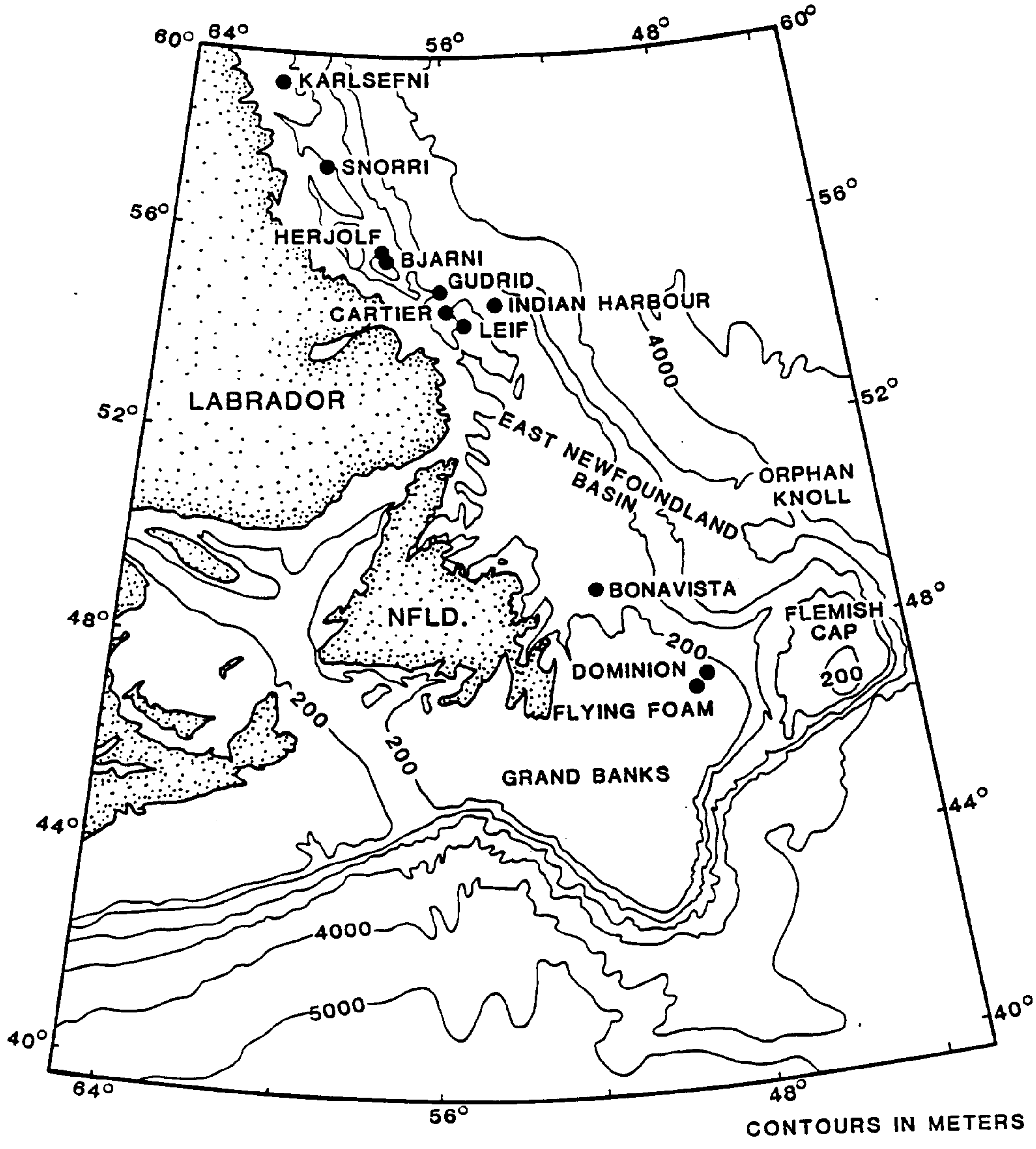


Figure 23. **SUBSIDENCE STUDY: LOCATION OF EXPLORATORY WELLS FROM OFFSHORE NORTHEASTERN CANADA**

Modified after Keen (1979)

pre-Triassic, i.e. Upper Devonian to Upper Carboniferous sedimentary rocks are known. Most of the Upper Paleozoic units and the overlaying Upper Triassic - Lower Jurassic sequences are bound by major unconformities.

The Upper Paleozoic and Upper Triassic - Lower Jurassic units appear to have been deposited in a tectonically differentiated setting with intermittent periods of epeirogenic activity interrupted by times of quiescence. In Late Jurassic the Grand Banks platform started to undergo another period of block faulting which culminated during the Early Cretaceous. The post-Avalon unconformity sediments are rather uniform and monotonous, indicating uniformity of depositional processes and quiescence of the platform. The late Cenozoic witnessed a slowing of the subsidence rate coupled with an increased influx of detrital material. This led to a general by-passing of the shelf on which little sediment was deposited, and a large mass-transfer to the shelf edge and its outbuilding into deep water. The progradation of the shelf edge led to another sediment mass-transfer to the base of the slope and the bathyal realm by gravity induced failures of the upper continental slope and the invasion of the deep water domain by slump masses and turbidity currents.

As in many other continental margins, the sedimentary rock thicknesses of the Grand Banks of Newfoundland are impressive, ranging from an estimated average of 8,000 to 10,000 m with recorded maxima over 14,000 m. The sub-unconformity basins themselves contain 5,000 to 8,000 m of sediment. This very thick accumulation took place in shallow water depositional environments, ranging from continental-paralic to fluvio-deltaic, marginal marine, shallow marine inner shelf and epicontinental sea settings. The early Cenozoic witnessed a deeper shelf environment and it was not until the late Cenozoic that a drastic change took place with the development of massive sedimentary transfer to the upper slope.

Salt diapirs are very common in the Grand Banks and were drilling targets during the early phase of petroleum exploration. They are known as far north as the Jeanne d'Arc Sub-basin and also the East Newfoundland Basin, but are absent from the Flemish Basin. They are thought to derive from two main stratigraphic units of Middle Carboniferous and Late Traissic - Early Jurassic age respectively.

Salt dome geometry is quite variable and covers a wide spectrum of structures: incipient deep dome warping of the Jurassic strata, higher level structures which do not reach or affect the Avalon Unconformity, structures which warp the unconformity without transgressing it, and higher piercement bodies which breach the unconformity and intrude the Upper Cretaceous - Tertiary rocks (Figure 15). High thermal conductivity and lateral heat transfer along salt diapir flanks have been linked to accelerated source rock maturation in studies from the Scotian Basin (Keen, 1983; Rashid and McAlary, 1977) and from the Jeanne d'Arc Sub-basin of the Grand Banks (Rashid, 1978).

Subsidence and Thermal Evolution

A large body of comparative theoretical modeling pertaining to the subsidence and thermal evolution of continental margin is available (refer to Beaumont et al., 1982 for a general review, and Keen and Barrett, 1981 for a review concerning eastern Canada). The article from Keen (1979) is the only recent paper specifically addressing these questions for the Grand Banks of Newfoundland, based on data from two closely spaced wells drilled in the

Jeanne d'Arc Sub-basin (Figure 24). It remains to be shown that the conclusions derived from the Jeanne d'Arc Sub-basin can be generalized to the entire Newfoundland Continental Margin.

According to the prevalent scenario of crustal evolution of a passive continental margin, as followed by Keen (1979), a high original heat flow is postulated during the early period of platform rifting, followed by a post rifting period of slow crustal cooling and concomitant passive crustal sinking (tectonic subsidence). The theoretical pattern of this thermal cooling model is a simple, linear relationship between the square root of time (since rifting) versus thermal subsidence. Tectonic subsidence should be calculated from the overall subsidence pattern derived from the stratigraphic record. It can be quantified, within some debatable methodologic limits, by removal of the subsidence effects due to sediment loading (preferably corrected for compaction) and water loading (eustatic sea level changes correction, Figure 25). Results from studies of the Scotian and Labrador Shelf show a good agreement with theoretical prediction (tectonic subsidence close to thermal subsidence), at least for the first 80 m.y. or so in the case of the Scotian Shelf. Data from the Jeanne d'Arc Sub-basin (Figure 24), although only computed from the Late Cretaceous - Paleocene, i.e. about one hundred m.y. after presumed inception of rifting, show a considerable variation from the linear relationship (Figure 26). The tectonic subsidence pattern departs from the thermal model and indicates a higher than predicted subsidence rate for the Paleocene - Eocene followed by a sharp decline and a lower than predicted rate for the Oligocene - Miocene. This last period was characterized by low sedimentary deposition and preservation on the Grand Banks Shelf and sediment by-pass to the shelf edge and slope. Such a departure from the passive thermal model was predictable when it is considered that the Grand Banks of Newfoundland continental margin is known to have undergone fragmentation during Late Cretaceous time.

Assuming the results from studies performed in Scotian Shelf can be extrapolated to offshore Newfoundland, the thermal modeling of Keen (1979) documents (within the bounds of some basic assumptions; in particular the margin is assumed to be close to equilibrium with little further subsidence) a crustal thinning of 12,000 m with respect to mainland crustal thickness. This conclusion is in agreement with the estimates obtained by Keen and Cordsen (1981) from deep seismic refraction studies. Subtracting the post-rifting sediments (9,000 to 16,000 m), the crust of the central Scotian Shelf appears to be 14,000 to 21,000 m thick versus 35,000 m beneath Nova Scotia, i.e. a crustal 'thinning' of the order of magnitude greater than 10,000 m.

Summary

The Atlantic continental margin of Newfoundland differs in an important respect when compared to the U.S. margin. Beyond the simple fact that the margin extends much further offshore than previously realized, it encompasses at its seaward outer periphery an array of downfaulted crustal blocks, now located at bathyal to abyssal depths. Notwithstanding the meager data base available, the foundering of part of the outer margin can be dated as an Early to Late Cretaceous event, based on data from DSDP Sites 111 and 384.

Since middle Late Cretaceous, the two DSDP sites appear to have been basically stable in deep water, in a regime of hemipelagic sedimentation and

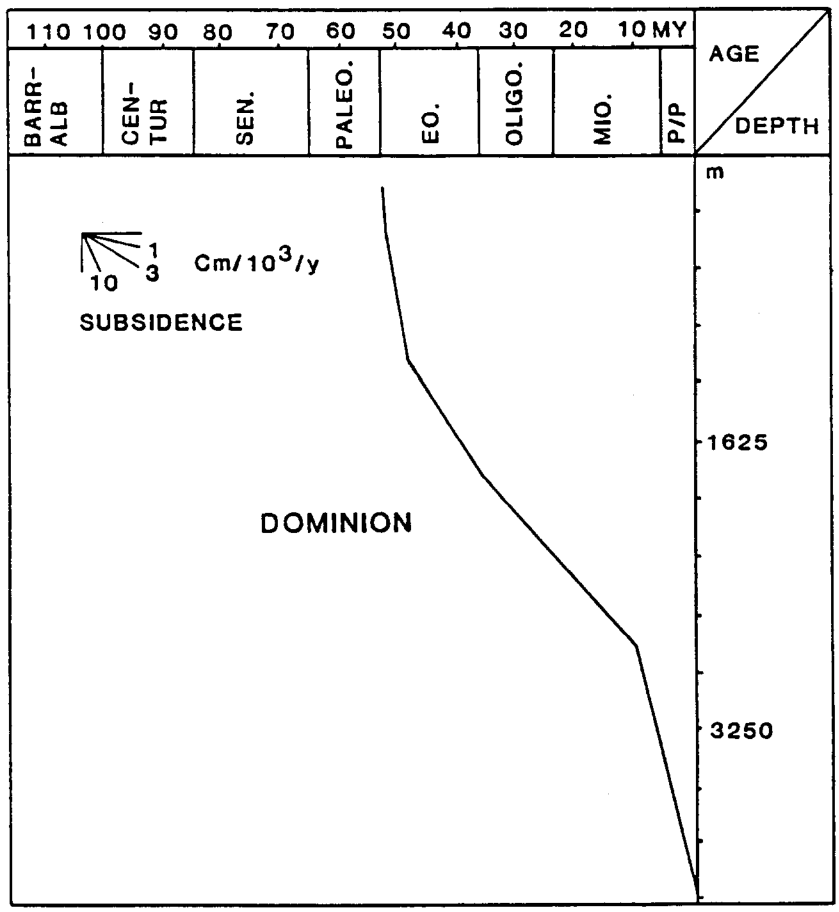


Figure 24. TOTAL SUBSIDENCE HISTORY FOR THE DOMINION EXPLORATORY WELL (UNCORRECTED FOR COMPACTION)

Modified after Gradstein and Srivastava (1980)

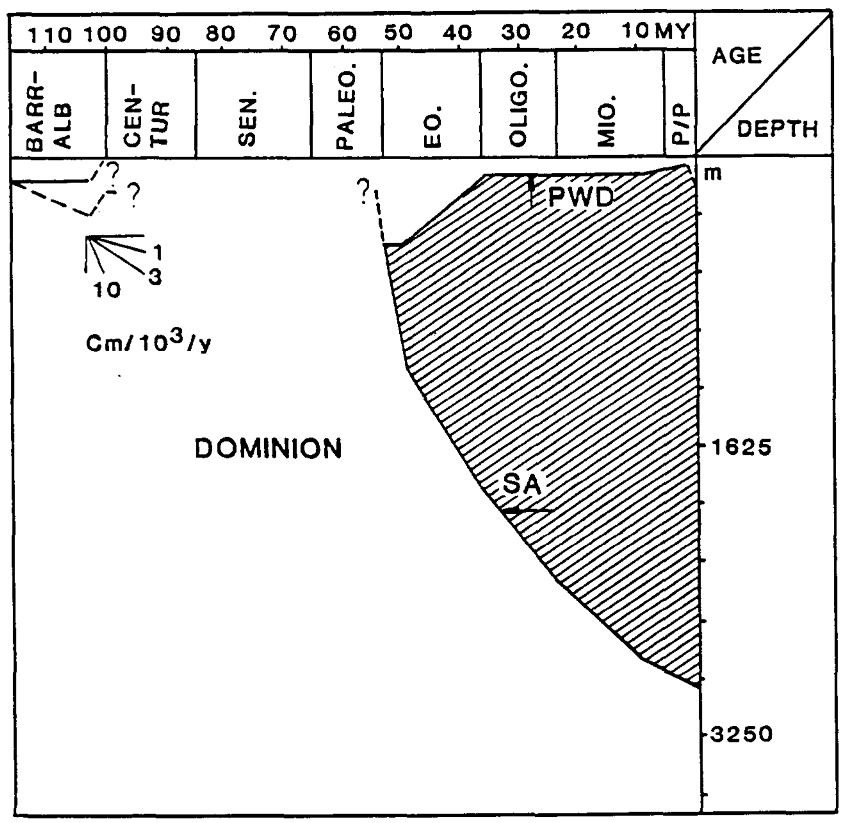
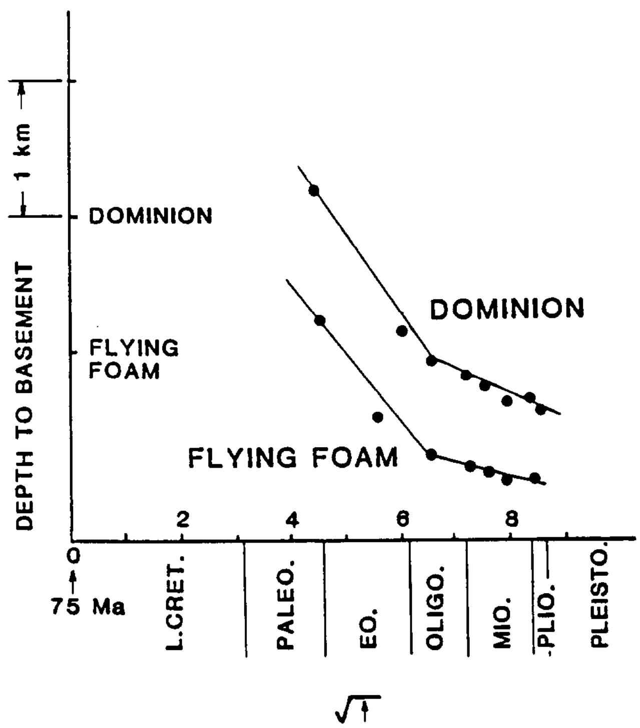


Figure 25. CUMULATIVE SEDIMENT ACCUMULATION (SA) PLOTTED AGAINST PALEOWATER DEPTH (PWD) THROUGH TIME FOR THE DOMINION EXPLORATORY WELL

Modified after Gradstein and Srivastava (1980)



TECTONIC SUBSIDENCE PLOTTED AGAINST THE
SQUARE ROOT OF TIME SINCE 75M.Y.

Figure 26. TECTONIC SUBSIDENCE CURVE FOR THE DOMINION AND FLYING FOAM EXPLORATORY WELLS (NORTHERN GRAND BANKS)

Modified after Keen (1979)

extended periods of current induced nondeposition. The scattered occurrences of Early Cretaceous shallow water limestones document the northern extension of a huge, discontinuous carbonate shelf along the eastern margin of the North American craton from the Bahamas to approximately 50° N latitude. The discovery of remnants of this platform from the offshore regions (J - Anomaly Ridge, Fogo Seamounts, southern Grand Banks, Newfoundland Seamount, Flemish Cap, and Orphan Knoll) are an indirect testimony to the pre-collapse outline of the former continental margin.

Discussion

The gas hydrate potential of the Grand Banks area would appear to be limited by the shallow water depth and thus low confining pressures on the sea bottom. Widespread, rich, mature source beds exist beneath the Avalon Unconformity. Fracturing associated with diapiric uplift should provide the migration conduits necessary for transfer of thermogenic gas to the sea floor. However, published stability diagrams suggest a minimum depth of gas hydrate occurrence of 300 to 400 m, negating the potential for gas hydrates in the Grand Banks area (Figure 27).

Recent work by the staff of Geoexplorers International suggests that thermogenic gas hydrates may be stable in the pressure and temperature conditions of the Grand Banks. A computer model of offshore gas hydrate stability using successive approximations to determine depth and thickness of stability zones has been developed in conjunction with work on the Gulf of Mexico (Krason et al., 1985, in preparation). Stability zones for the model were defined using the dissociation values of Holder and Johns as tabulated by Kuuskraa et al. (1983). The stability equations were modified for salinity using data from Scott et al. (1980) and the Gas Research Institute (1979). The model is dependent on the extrapolation of laboratory data to natural environments which may introduce substantial error into the calculations. The model agrees with the accepted notion that 200 m is too shallow to stabilize biogenic methane hydrate under the bottom temperature and geothermal gradients common on the Grand Banks. However, thermogenic gas hydrates should be stable to depths of near 100 m depending on the boundary conditions specified. Thus, large areas of the Grand Banks may be favorable for gas hydrates if an efficient migration mechanism can saturate pore waters with sufficient gas to initiate and maintain crystallization.

No BSRs were located on salt diapirs on the Grand Banks. In the Gulf of Mexico thermogenic gas hydrates have been recovered on the flanks of diapirs in the absence of BSRs. BSR detection on the Grand Banks is complicated by the shallow water depth which places the sea floor multiple, another unconformable reflector which follows bottom contours, within the depth range expected for hydrate BSRs.

Generally, it appears that, similarly to the continental margin of the U.S. Atlantic Coast, the continental slope of Offshore Newfoundland is the best area for gas hydrate occurrences. The fact that, contrary to the case of the U.S. Atlantic Coast, the continental slope offshore of Newfoundland is underlain by thick sedimentary prisms with possible hydrocarbon generative capacity, makes it a reasonably attractive target for gas hydrates. However, the only BSR recorded offshore of Newfoundland is located north of Flemish Cap (See Figure 1; Kenard and Coffman, pers. commun., in Taylor et al.,

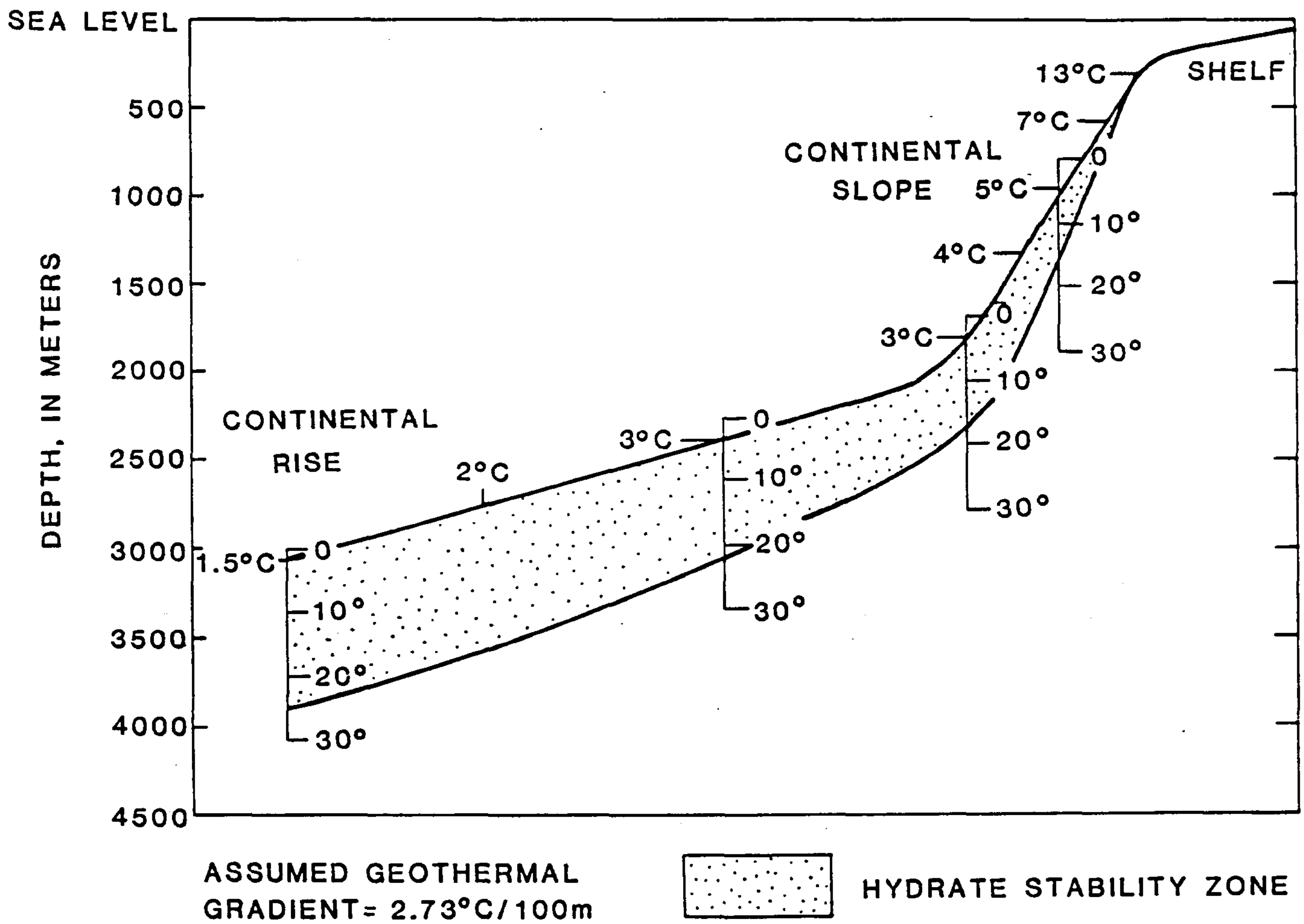


Figure 27. ZONE OF GAS HYDRATE STABILITY FOR CONTINENTAL MARGINS

Modified after Kvenvolden (1983)

1979), presumably in 2,000 m water depth and appears to fit the above stated generalization. The hydrocarbon generative capacity of the two DSDP sites, i.e. sites 111 and 384, are briefly reviewed below and the result of this short analysis are discouraging. A generalization, if warranted from this meager data base, conflicts with the previous inferrence regarding deep seated gas prone sedimentary sections under the continental slope of the margin.

Lithologically, the Cenozoic sediments at DSDP Site 111 (Orphan Knoll) are most likely to produce biogenic methane, being composed largely of hemipelagic muds and interbedded sands and silts. The Cretaceous sediments are chalks and have a negligible gas potential.

No organic matter data are available. Based on the color descriptions of Tertiary and Quaternary muds, only a few have a significant organic component (Laughton et al., 1972). These are as follows:

- at 140 m sub-bottom, 1 m dark grey clay bed with black streaks (Pliocene).
- at 147 m sub-bottom, a 3 cm black reduced clay layer (Miocene or Eocene).
- at 160 m sub-bottom, a 5 cm black clay layer (early Eocene).
- at 170 m sub-bottom, laminated marls with dark clayey streaks (early Eocene) .

The remaining clay sediments are light colored.

The rates of sediment influx are estimated as follows:
Pleistocene: 10mg/cm^2/yr
Late Pliocene: 2.9 mg/cm^2/yr
Early Pliocene: 0.06 mg/cm^2/yr

Assumed sediment porosity is 40%; all the above listed values are very low and suggest that sediment influx rate is not a factor in producing anoxic conditions. This is consistent with the apparently oxidized nature of the sediments and the lack of a noticeable change in the pore water sulfate profile with depth (Manheim et al, 1972).

At Site 384, J - Anomaly Ridge, the total organic carbon (TOC) concentrations have been measured by Cameron (1983) using a LECO Analyzer, throughout the cored Mesozoic - Cenozoic interval. The results are discouraging with regard to organic carbon. Only one sample showed 0.1% TOC; in the remainder, organic carbon was not detected. Therefore it seems very unlikely that at Site 384, there can be a reasonable source of biogenic methane for hydrate generation.

East Newfoundland Basin and the Southernmost Labrador Shelf

The East Newfoundland Basin and the southern part of the Labrador Shelf cover approximatively 300,000 km^2. This vast offshore area can be delimited between 47° N and 53° N latitude and from the shallow shelf area of the northern coast of Newfoundland on the west side to Orphan Knoll (46°20' W longitude) and Flemish Cap (45° W longitude) on the east side (Figure 28).

A broadly defined composite basin known as the East Newfoundland Basin (also referred to in the literature as the Newfoundland or the Avalon Basin) also encompasses the whole area inshore of Orphan Knoll. The southernmost part of the Labrador Shelf is also incorporated within that area. It is underlain by the large Belle Isle Arch (also known as the Cartwright Arch) which separates the northwestern extention of the East Newfoundland Basin (Belle Isle Sub-basin) from the Hopedale Basin of the south-central Labrador continental margin (Figure 4).

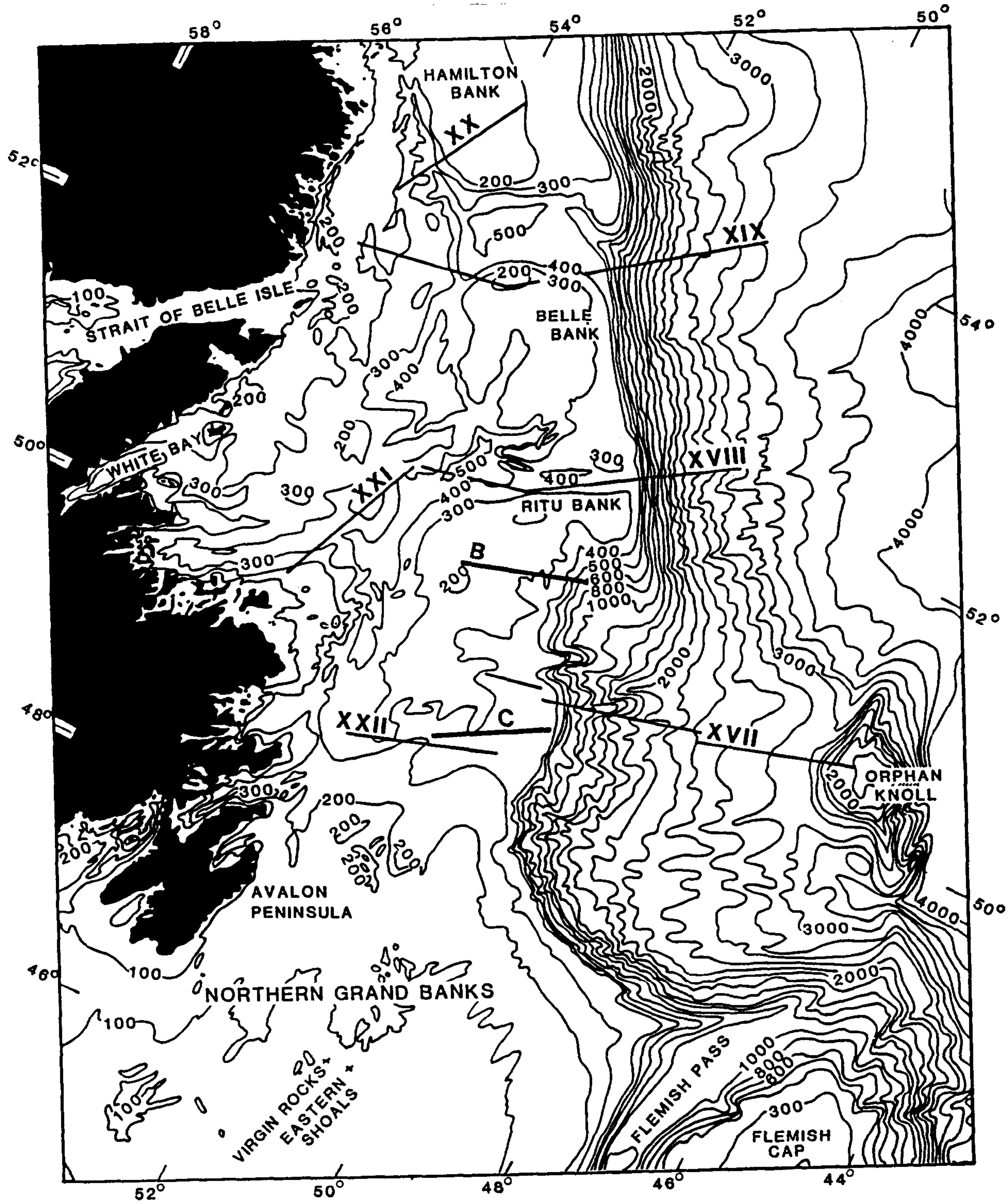
The East Newfoundland Basin is in fairly deep water, its eastern half lying under an average water depth of 2,000 m. The deep waters have precluded significant exploration for hydrocarbons in this basin. Five wells have been drilled to the end of 1983 in the western shallower half of the basin in water depth not exceeding 1,000 m.

A serious data gap precludes an in-depth discussion on the geology of this basin. Similarly, there is no information pertinent to gas hydrate potential evaluation. Also no BSRs are reported from the seismic profiles. Based on the pressure - temperature gas hydrate stability field and known worldwide offshore gas hydrate occurrences (Kvenvolden and Barnard, 1983) that this deep water, large basin should present a reasonable potential, especially when compared to the Grand Banks of Newfoundland.

The data presented in this chapter are organized and discussed under two headings: the East Newfoundland Basin for the central and eastern areas north of the Grand Banks and a western East Newfoundland Basin for its western shallower part.

Tectonics and Stratigraphy

East Newfoundland Basin. In the East Newfoundland Basin the total sedimentary thickness reaches 8,000 m in the central axis of the basin (Figure 13); accumulations in excess of 14,000 m are seismically inferred. A pattern of northwest trending basement ridges and sedimentary troughs (Jansa and Wade, 1975) suggesting a foundered, block-faulted continental crust similar to that of the Grand Banks has been documented by numerous authors (Grant, 1975; Haworth, 1977; Procter et al., 1983; Figure 29). A block-faulted sub-basin configuration characterizes the lowest seismic interval. Carboniferous carbonates and clastics have been encountered on a structural high by the most easterly well drilled in the basin (Procter, 1983). It is inferred that thicker Paleozoic sequences and also Jurassic - Early Cretaceous strata are located in the downfaulted blocks of this basin. The section encountered by the aforementioned well shows a major depositional hiatus above the Carboniferous strata followed by deposition of an Aptian - early Cenomanian shale



LEGEND

CONTOURS IN METERS

—— DIAGRAMMATIC SEISMIC PROFILE LOCATION · XVII THROUGH XXII

—— SEISMIC SECTION LOCATION · B AND C

Figure 28. BATHYMETRIC MAP OF OFFSHORE NORTH-NORTHEASTERN NEWFOUNDLAND AND SOUTHERNMOST LABRADOR WITH LOCATION OF DIAGRAMMATIC SEISMIC PROFILES AND SECTIONS

Modified after Grant (1972)

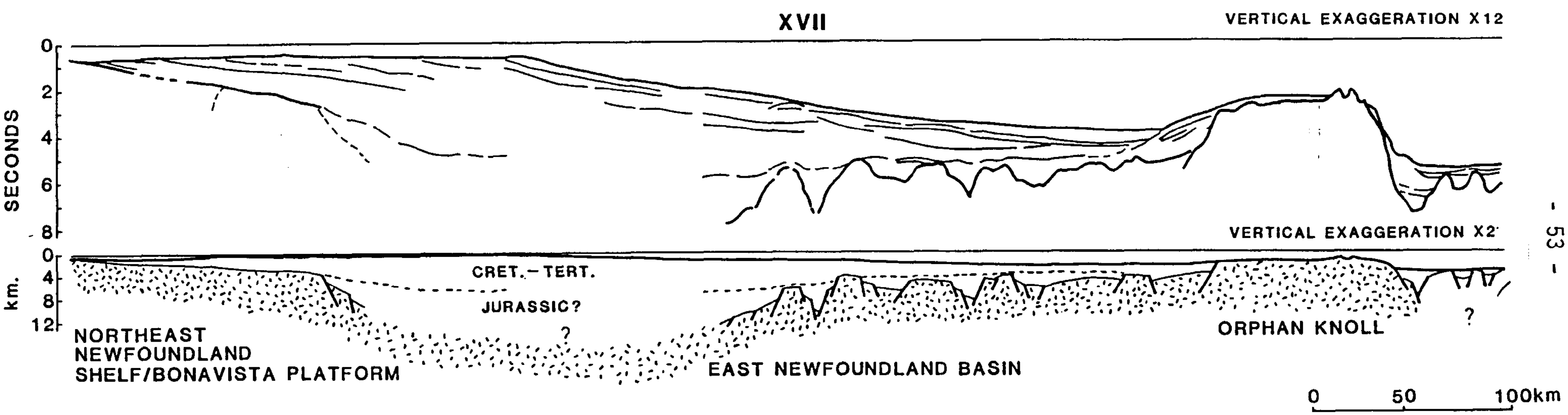


Figure 29. DIAGRAMMATIC SEISMIC PROFILE AND GEOLOGIC INTERPRETATION THROUGH THE EAST NEWFOUNDLAND BASIN

Modified after Grant (1975)

and sandstone unit. Another prolonged hiatus was followed by Upper Cretaceous, chalk type strata interpreted as deep water deposits. These sediments are succeeded by an Eocene - early Oligocene marl, mudstone and sandstone sequence and by late Cenozoic clastics, following a Miocene hiatus. This stratigraphic section, although unique, does not shed much light on the geologic evolution of the basin. The sediments have been found on top of a basement high, and more complete and thicker sections are inferred seismically from the troughs. The overall impression, combined with the nearest drill data, known from the Jeanne d'Arc Sub-basin and Orphan Knoll, is of a block-faulted tectonic pattern, which affected sedimentation until the Early Cretaceous. The Avalon Unconformity of the Grand Banks, which is also developed on the flanks of the Jeanne d'Arc Sub-basin, slowly fades away seismically in the basinal areas of the East Newfoundland Basin and passes into paraconformable to conformable relationships. The post-Avalon unconformity sediments (Late Cretaceous to Tertiary) appear to have been unaffected by the block-faulting tectonics which blanket the basin, forming in a very generalized way, a great sediment wedge tapering from west to east.

No information is available regarding the Quaternary deposits. The topography of the sea floor under 2,000 m of water is very irregular and is attributed to slumping processes and turbidity and bottom current action.

Western East Newfoundland Basin - Bonavista Platform. The western portion of the East Newfoundland Basin which lies in fairly shallow water (400 m average) has also been sparsely drilled (Figure 28). This section of the report is based upon the 1977 paper by Cutt and Laving. Seismic stratigraphic interpretation permits the delineation of the three following "seismic sequences" (Figures 30 and 31):

- an upper, relatively undeformed seismic sequence (unit 3), restricted to the northern part of the basin, south of the Belle Isle Arch. It rests unconformably on older units and is inferred to represent Jurassic - Lower Cretaceous, pre-unconformity strata.
- a second seismic unit (unit 2) interpreted as carbonates and evaporites of late Paleozoic (undivided) age. Salt diapirs are known from the axis of the northwest trending Belle Isle Sub-basin.
- a lower sequence (unit 1) inferred to represent northward extention of onshore basement rocks.

The Avalon unconformity seismic event seems to be identifiable in an attenuated way through some parts of the basin, although there is some conflicting evidence. It reappears as a major seismic feature south of the Belle Isle Arch, which was transgressed by clastic sediments during the Late Cretaceous and remained active as a positive feature during the Eocene. The upper seismic unit represents the thick post-unconformity clastic sequence of Late Cretaceous - Tertiary age. These strata blanket the basin, and rest upon a block-faulted substratum.

The Pleistocene deposits south of Hamilton Inlet (southernmost Labrador Shelf) become more complex. This could be due to the widening of the continental shelf (Grant, 1972). The morainal deposits of the continental shelf, northeast of Newfoundland, were deposited in deeper water than those off the

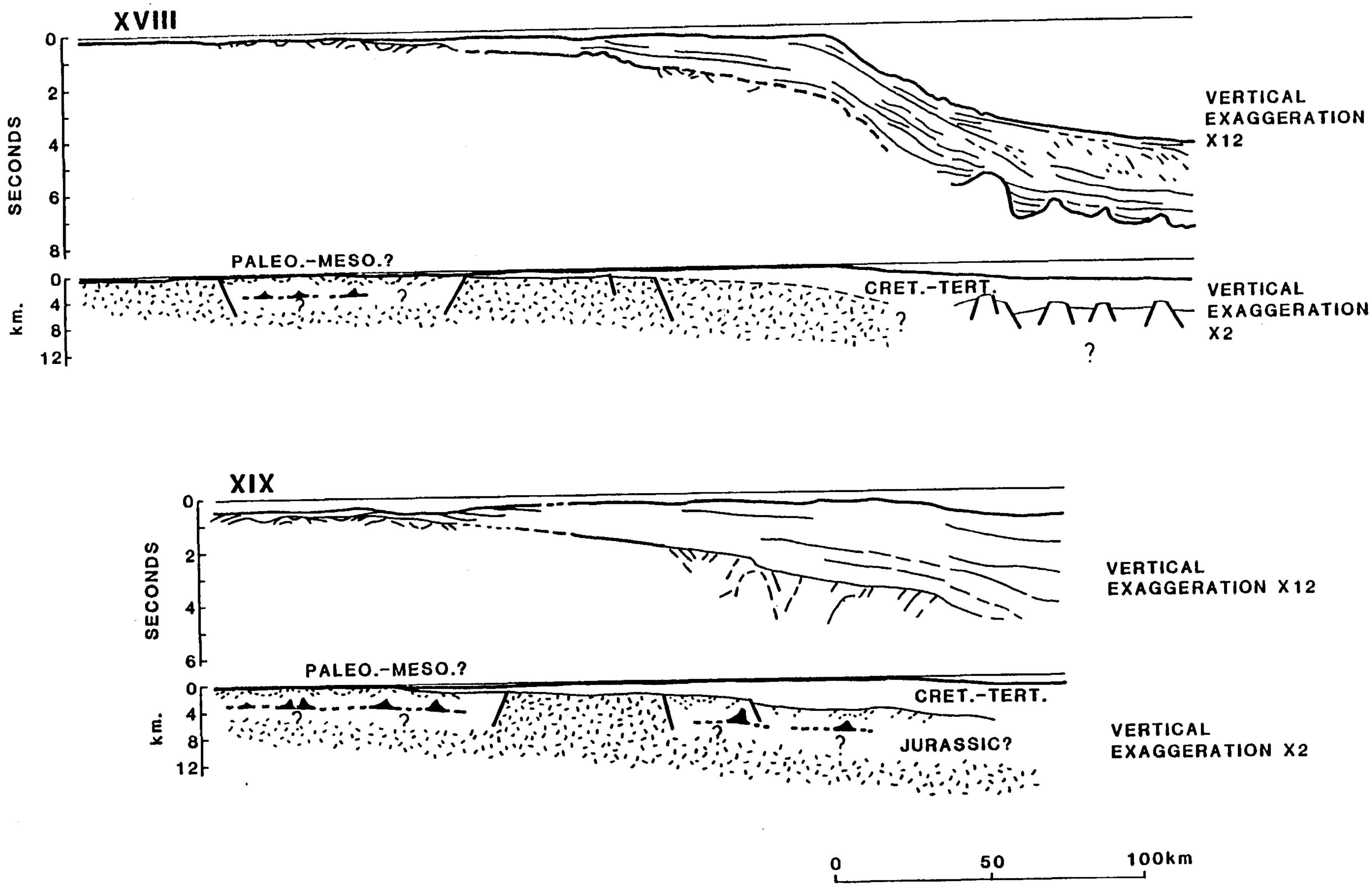


Figure 30. DIAGRAMMATIC SEISMIC PROFILES AND GEOLOGIC INTERPRETATION THROUGH THE NORTHERN NEWFOUNDLAND AND SOUTHERN LABRADOR SHELVES

Modified after Grant (1975)

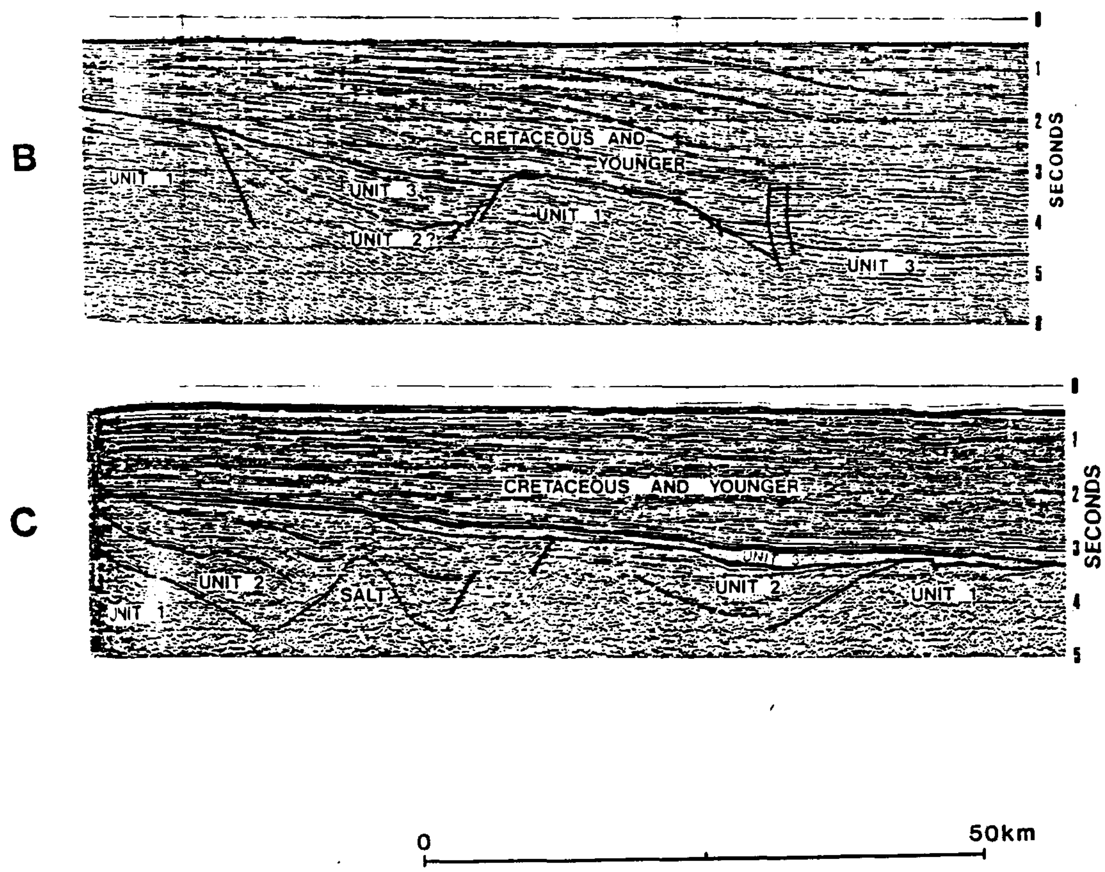


Figure 31. SEISMIC SECTIONS THROUGH THE NORTHWESTERN AND WESTERN PART OF THE EAST NEWFOUNDLAND BASIN

After Cutt and Loving (1977)

Labrador coast and the Grand Banks. Their more pronounced physiographic expression and better defined internal structure indicate that they have undergone less severe, post-deposition reworking. Relict sediments appear to be common. Drift cover is generally thin over the inner part of the outer banks, averaging 20 m or less in thickness. Toward the shelf edge occur glacial outwash deposits. Some of the eastern parts of the banks bear a cover of unconsolidated sediments approximatively 100 m thick. A late Pliocene - early Pleistocene angular unconformity has been documented in the central area of the shelf; accumulations of glacial drift (over 100 m thick) rest on truncated strata (Figure 32). The declivity of the continental slope to the northeast of Newfoundland is very gradual. In this region shallow seismic profiles consistently show the presence of a buried unconformity near the edge of the shelf and truncation of near horizontal reflectors along the slope.

Petroleum Geology

The block faulting extensional tectonics which affected the Grand Banks in middle Early Cretaceous time is also the dominant feature of the East Newfoundland Basin, although it is not as firmly time constrained as in the northern Grand Banks area. The configuration of the deep basin consists of pre-late Cretaceous basement horsts ('ridges') and grabens (Cutt and Laving, 1977; Jansa and Wade, 1975; McWhae, 1980; Procter et al., 1983) (Figures 29 - 31). A large array of potentially interesting structural traps similar in nature to the ones known from the northern part of the Jeanne d'Arc Sub-basin are inferred to be present: draping over basement highs and salt structures, tilted fault blocks and possibly roll-over domal features.

Subsidence and Thermal Evolution

Data from a single well (Bonavista), located in the southern part of the northeastern Newfoundland Shelf, indicate a post-Late Cretaceous subsidence pattern in poor accordance with the $t^{\frac{1}{2}}$ thermal relationship (Keen, 1979). In detail, departures from the theoretical model are noticeable: slow subsidence during Maestrichtian - Paleocene time, then an accelerated rate during the Eocene - Oligocene, followed again by a slow rate during the Miocene - Pliocene (Figures 33 - 35). This latest subsidence phase mirrors in a somewhat attenuated way the drastic decline in subsidence documented from the Grand Banks for the same period of time.

Discussion

The only seismic BSR known from the offshore area of Newfoundland is reported from an area north of Flemish Cap (Kenard and Coffman, pers. commun., in Taylor et al., 1979), presumably in 2,000 m of water (DOE information), might conceivably occur in the eastern part of the East Newfoundland Basin. The seismic section(s) from which a BSR has been reported are proprietary (Imperial Oil Co., a subsidiary of Exxon). The general depth and the inferred widespread occurrence of recently deposited sediments (slumping, turbidity current) are both propitious characteristics with respect to gas hydrate potential.

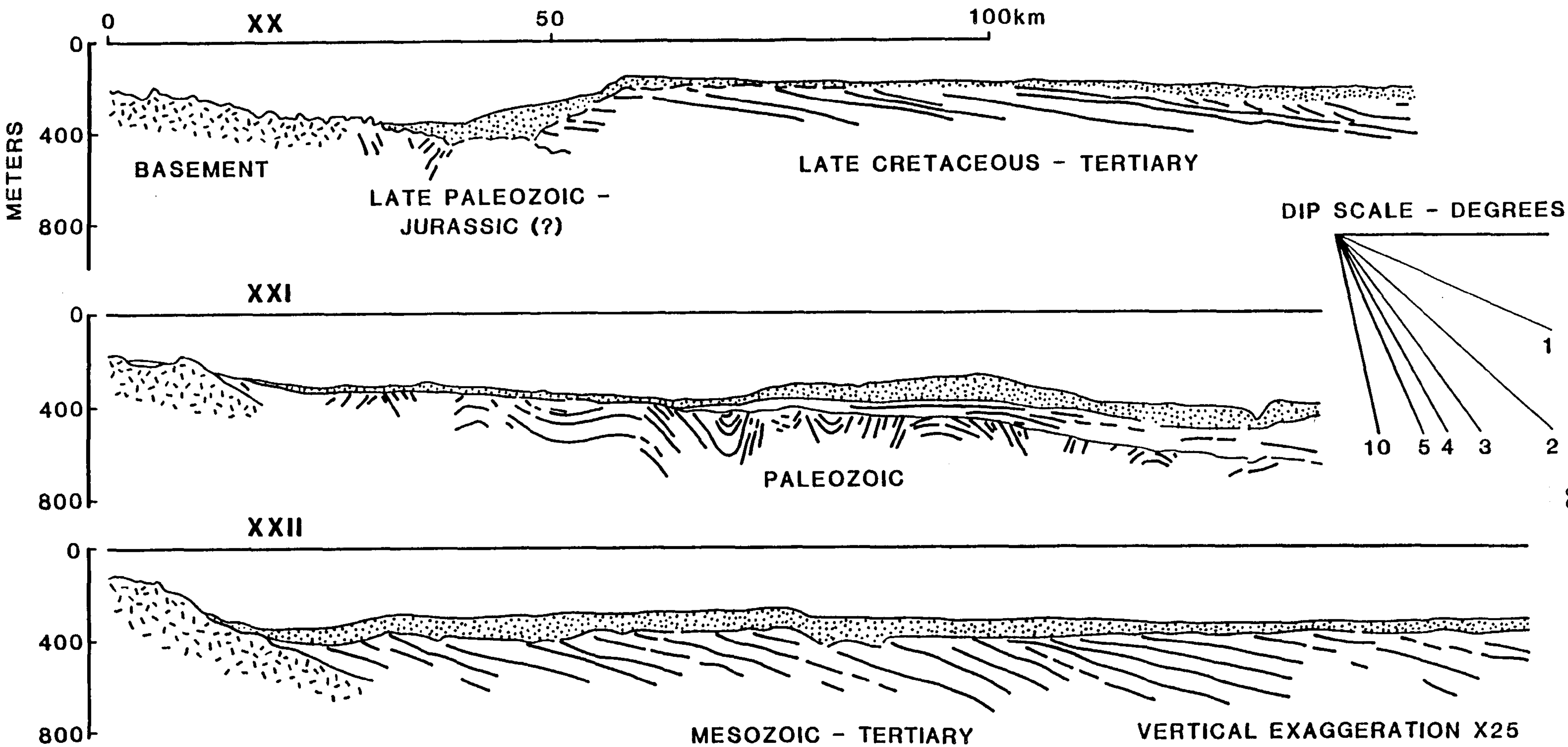
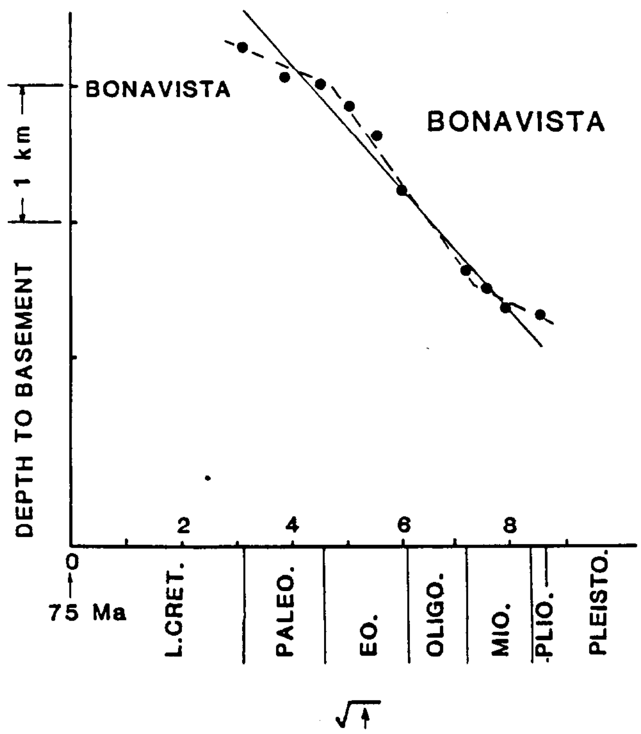


Figure 32. SHALLOW DIAGRAMMATIC SEISMIC PROFILES THROUGH THE NORTHERN NEWFOUNDLAND AND SOUTHERN LABRADOR SHELVES

Modified after Grant (1972)



TECTONIC SUBSIDENCE PLOTTED AGAINST THE SQUARE ROOT OF TIME SINCE 75M.Y.

Figure 33. TECTONIC SUBSIDENCE CURVE FOR THE BONAVISTA EXPLORATORY WELL

Modified after Keen (1979)

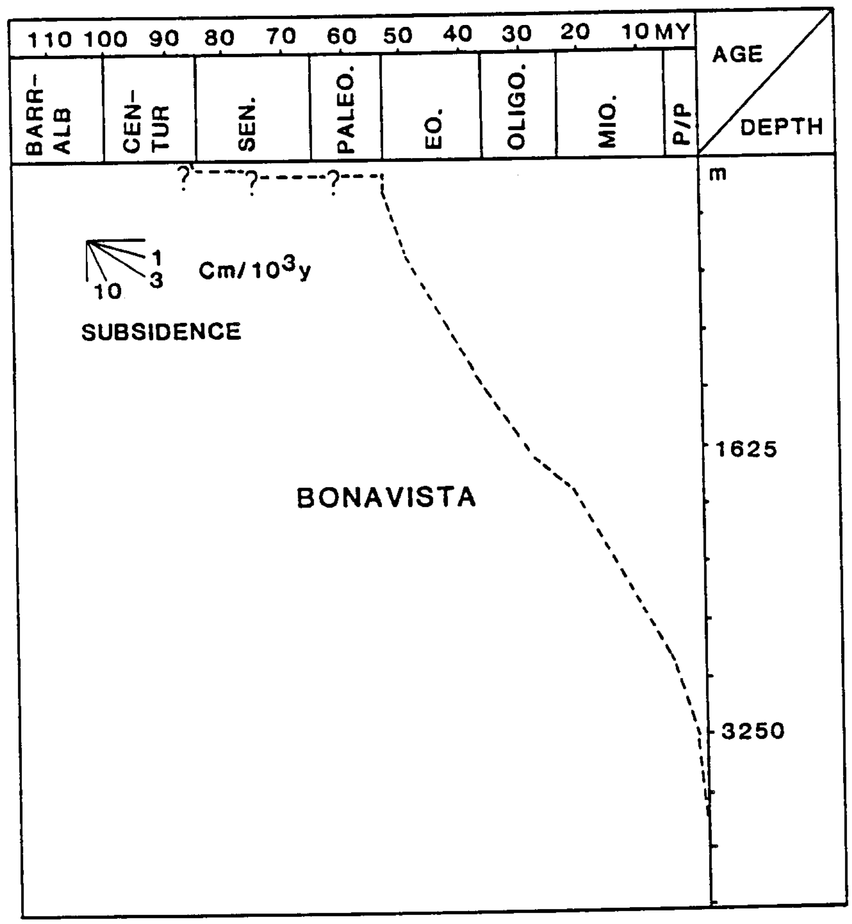


Figure 34. TOTAL SUBSIDENCE HISTORY FOR THE BONAVISTA EXPLORATORY WELL (UNCORRECTED FOR COMPACTION)

Modified after Gradstein and Srivastava (1980)

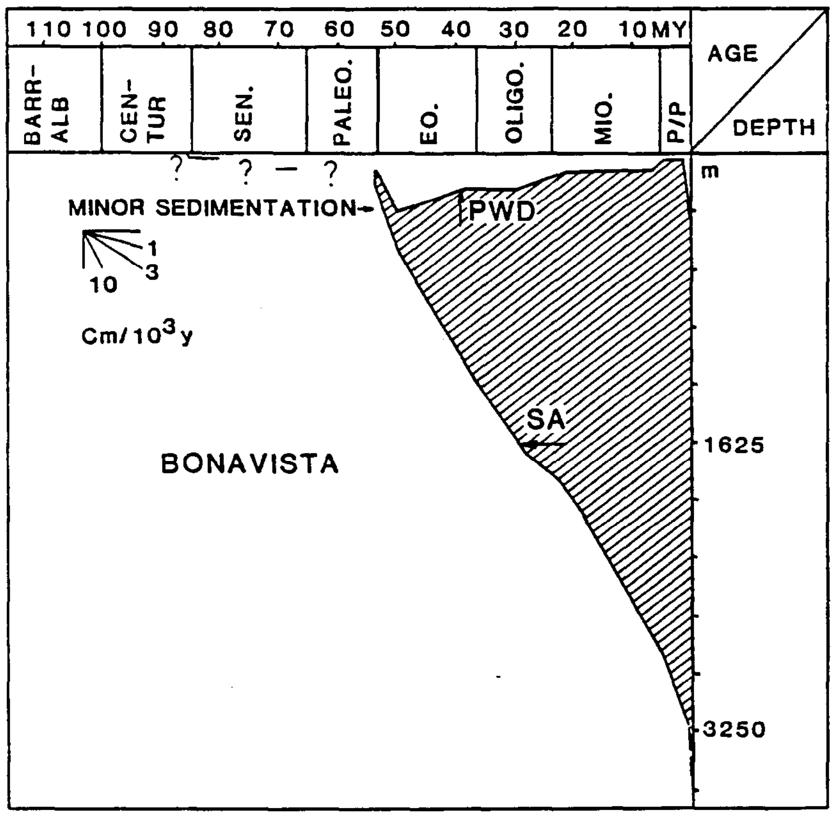


Figure 35. CUMULATIVE SEDIMENT ACCUMULATION (SA) PLOTTED AGAINST PALEOWATER DEPTH (PWD) THROUGH TIME FOR THE BONAVISTA EXPLORATORY WELL

Modified after Gradstein and Srivastava (1980)

Offshore Labrador

The sea floor of the large area offshore of the Labrador Peninsula is readily divided on geomorphologic grounds into a shallow shelf, an outer shelf - slope transition and an offshore Labrador Basin. The Labrador Shelf and the outer shelf-slope-basin shall be treated as two separate geologic entities.

Tectonics and Stratigraphy

Labrador Shelf. The shelf offshore of the large Labrador Peninsula extends approximatively from 53° N to 61° N latitude, with an average width of 200 km, and covers approximatively 200,000 km^2. This is a glaciated shelf (van der Linden, 1974; McMillan, 1973) of moderate average depth (80 m to 200 m) dissected by channels, normal to the coastline. The most important channels are separated by large banks (Figure 36).

Although no direct evidence of gas hydrates is reported from the Labrador Shelf, the presence of relict gas hydrates from the Pleistocene appear to be a possibility (Taylor et al., 1979). Biogenic methane has been reported from Pleistocene muddy sediments (Vilks et al., 1974) and rapid degassing of piston-core sediments has been reported from various localities. Although the present water depth is too shallow to stabilize gas hydrates, the presence of some metastable relict horizons is a reasonable assumption. These questions are addressed in the appropriate final chapter of this report.

The sedimentary rocks of the Labrador Shelf do not outcrop onshore. The submarine edge of the sedimentary prism occurs offshore and is marked by an ice-excavated depression, known as the Labrador Marginal Trough (Grant, 1972) which runs parallel to the coastline.

The thickness of the offshore sedimentary wedge ranges from zero at its western erosional edge, located along the Labrador Marginal Trough, to 8,000 m some 50 km offshore in the axis of the Saglek Basin (Figures 37 and 38).

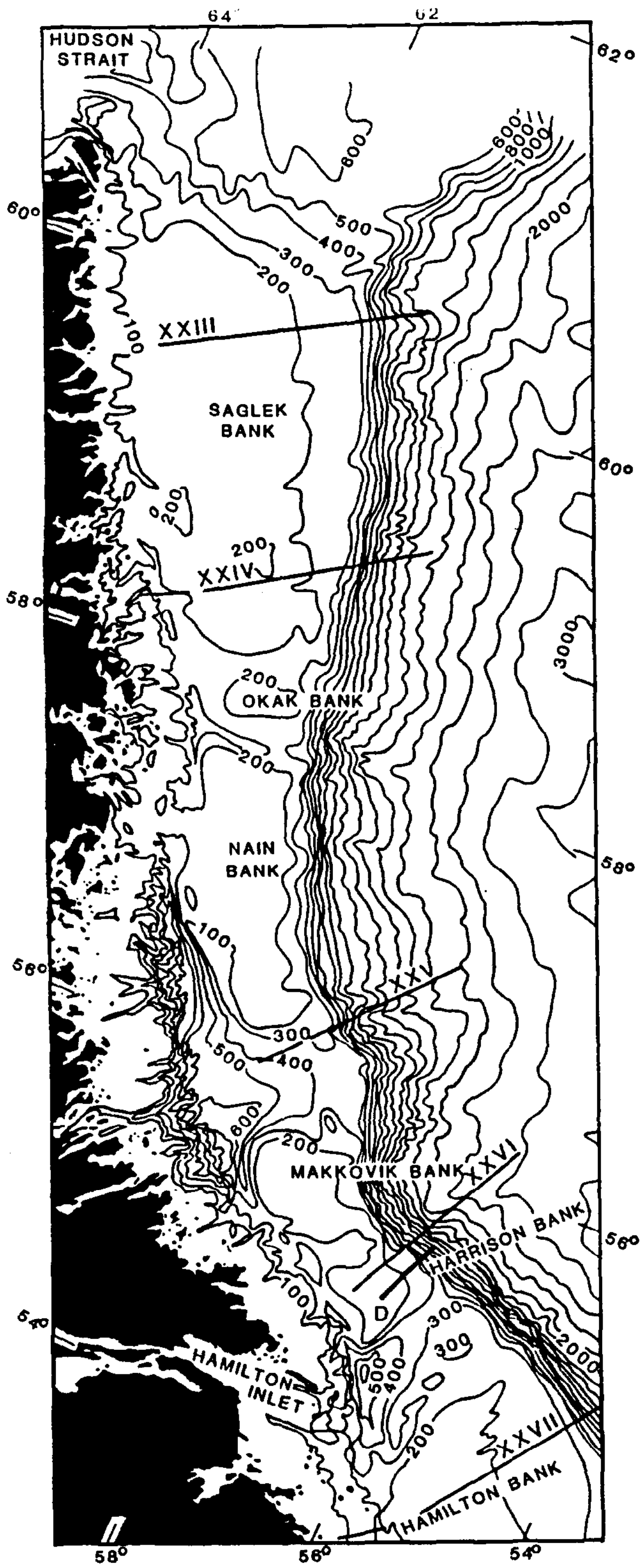
Most of the information used in the following discussion is derived from papers by Umpleby (1979) and McWhae et al. (1980).

Basement. The onshore crystalline basement of the Labrador Shelf consists of rocks of Precambrian age.

Undivided Paleozoic. The presence of Paleozoic sedimentary rocks, inferred from dredged pebbles, has been confirmed by drilling. Wells drilled near 54° N latitude have encountered Ordovician shelf carbonates, Carboniferous clastics and carbonates. These Paleozoic platform sediments occur discontinuously and are possibly preserved in graben type structures or as monoclinal cover of uplifted blocks.

Jurassic. The presence of Jurassic rocks is inferred from marl pebbles dredged from the north-central part of the shelf.

Early Cretaceous. The lower section of the shelf sequence, which is moderately well documented, begins with Early Cretaceous (Berriasian - Valanginian to Barremian) continental basaltic flows and epiclastic equivalent rocks which are known to rest on crystalline basement or upon the late



—— DIAGRAMMATIC SEISMIC PROFILE LOCATION · XXIII THROUGH XXVII
━━ SEISMIC SECTION LOCATION · D

Figure 36. BATHYMETRIC MAP OFFSHORE NORTHERN AND CENTRAL LABRADOR WITH LOCATION OF DIAGRAMMATIC SEISMIC PROFILE AND SECTIONS

Modified after Grant (1972)

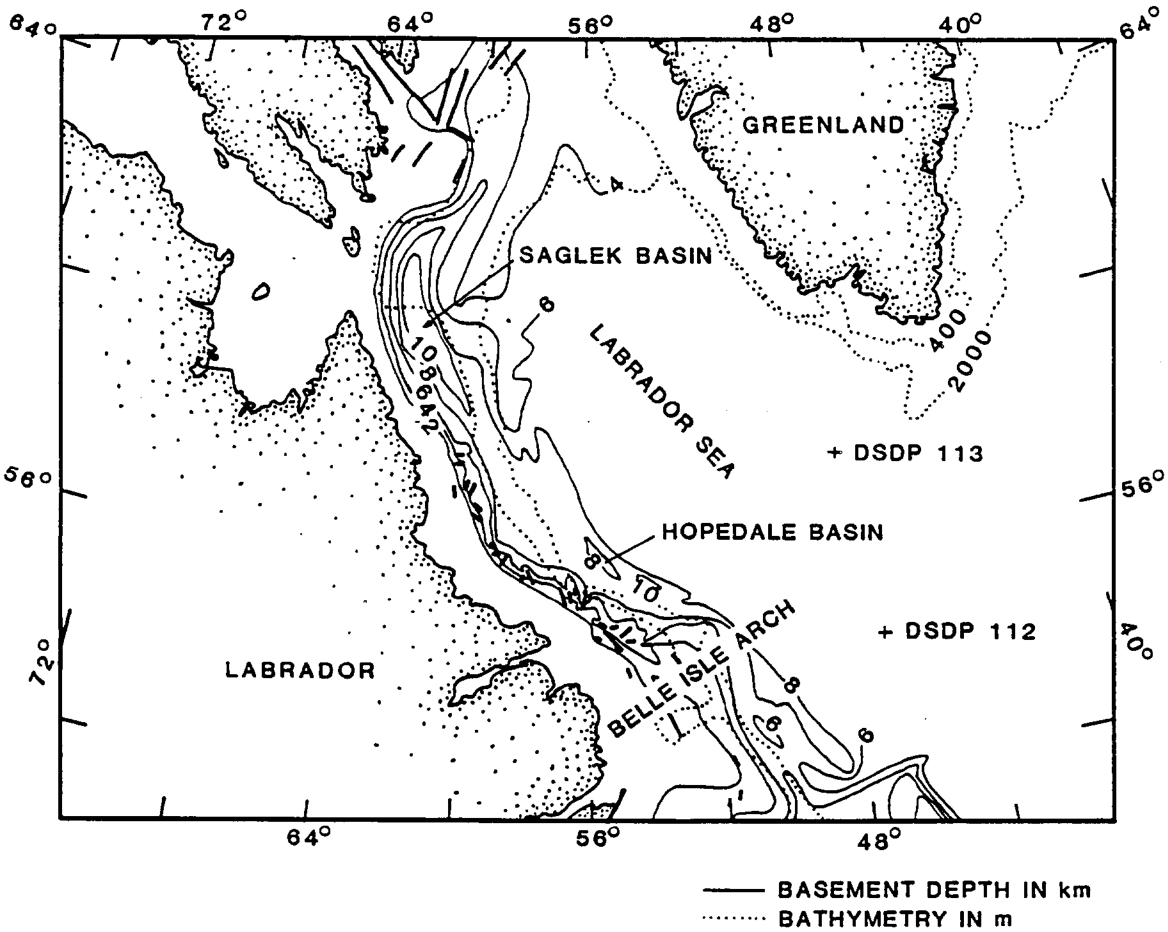


Figure 37. **DEPTH TO BASEMENT MAP AND BASIN CONFIGURATION OFFSHORE LABRADOR**

Modified after Grant, 1975

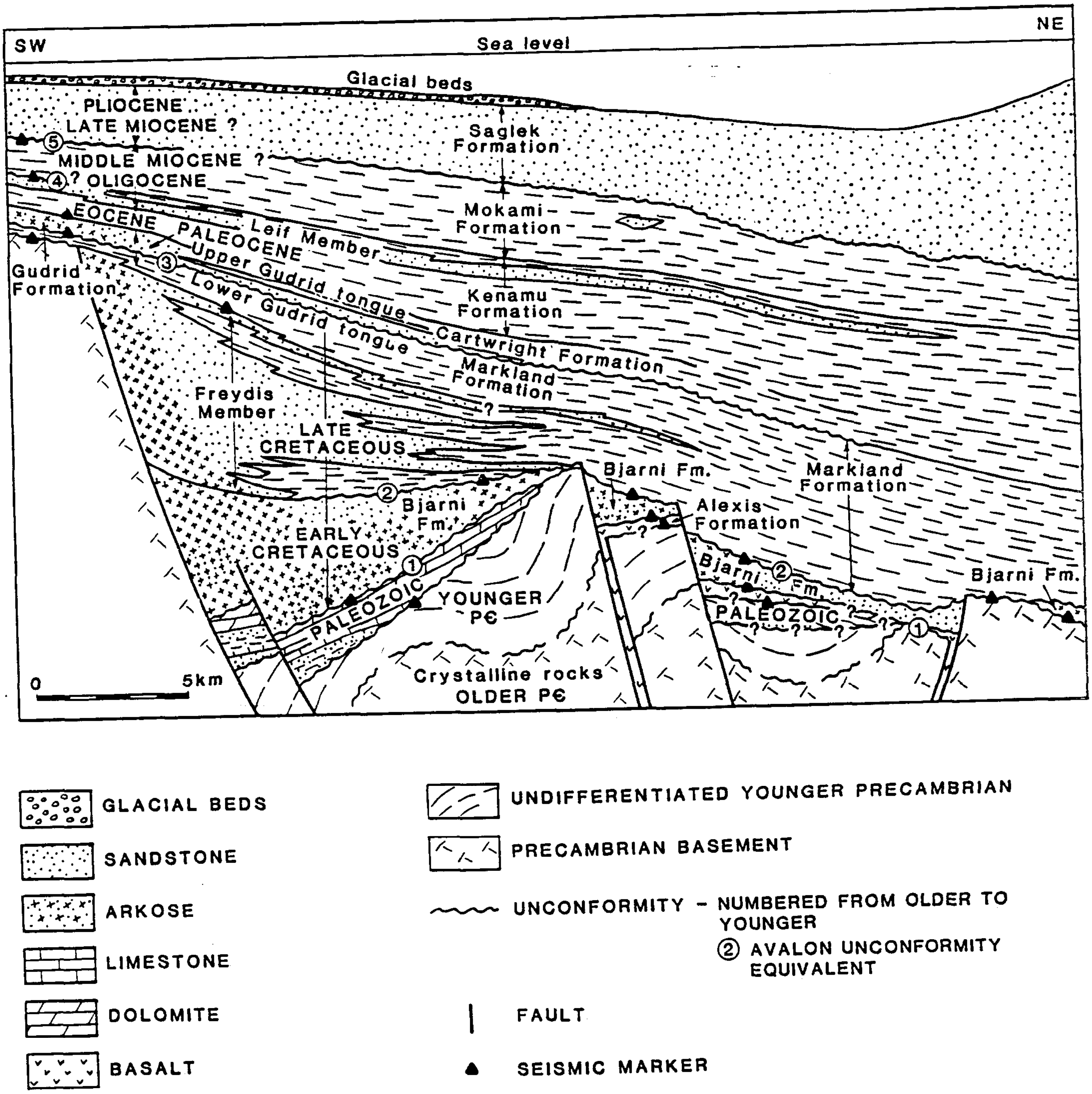


Figure 38. CONCEPTUAL CROSS SECTION OF THE NORTH-CENTRAL LABARADOR CONTINENTAL MARGIN

Modified after McWhae et al. (1980)

Paleozoic sedimentary units. The aggregate thickness of these flows is extremely variable (250 m are recorded from one well).

This volcanic unit is overlain in the south-central part of the shelf by a greywacke feldspathic sandstone and shale deltaic sequence with subordinated coal seams of late Early Cretaceous age (Barremian - Albian). The sequence has been interpreted as syn-rift and is indeed separated from the overlying unit by a regional unconformity, well expressed on seismic profiles (Figure 39). This unconformable event appears to be broadly coeval with the Avalon Unconformity of the Grand Banks, i.e. late Early Cretaceous time.

Late Cretaceous. The post-unconformity sedimentary sequence dated at its base as Cenomanian is made up of a monotonous sequence of shales and silty shales, spanning the Late Cretaceous and earliest Paleocene, and resting on an eroded composite substratum. In one of the farthest offshore wells, basaltic flows have been encountered at the level of the unconformity reflector. The marine sequence is interpreted as an outer shelf, pro-deltaic assemblage, deposited distally from a poorly developed, sandy deltaic sequence, encountered in some nearshore wells.

Tertiary. The Tertiary witnessed a marine transgression on the Labrador Shelf, basin deepening and upbuilding and progradation of the shelf margin concomitant with an increase of clastic material (Figures 40 - 43). A thick mudstone and siltstone sequence interrupted by thin turbidite sandstones was deposited and is interpreted as outer fan sediments grading westward into a glauconitic turbiditic sandstone unit. This thick uniform mudstone, siltstone fan complex was progressively built up to shallower water depth and is overlain by late Eocene, earliest Oligocene marginal marine, coal-bearing sandstones. Although the age of the sediments are poorly constrained, the Oligocene section appears to be very thin. In the late Oligocene - early Miocene, higher subsidence rate, deepening water, rapid sedimentation and rapid outbuilding and progradation of the shelf margin over the continental slope resumed. On the shelf, a thick sequence of "neritic" claystone is followed by a thick littoral to shallow neritic clastic series of mid to late Miocene to Pliocene age. Thin lignitic beds, glauconite grains and marine shell fragments attest to the littoral-marginal marine characters of these sandstones. Steepening of the shelf edge caused large scale mass transfer of sediments seaward, as slide, slump, debris flow and turbidity flow processes, thus leading to the thick Labrador Sea basin sequence.

The Miocene renewal of subsidence and rapid sedimentation was not a uniform process as indicated by differences in sediment accumulation, between the northern and south-central parts of the shelf, but followed a precursor Eocene pattern. The disparities in post-Paleocene sedimentary thicknesses between the northern shelf (Saglek Basin - maximum of 9,000 m of sediment) and the south-central shelf (Hopedale Basin - 5,000 m of sediment) are marked. This differential pattern is also noticeable for the Pleistocene glacial drift.

The late Tertiary was also the time of shale diapirism, which took place locally beneath the present continental rise. These diapirs originated from Eocene mudstones and are due to the rapid burial of water-laden sediments and the hindrance of normal dewatering leading to overpressurization.

The timing of late Tertiary sedimentation is not well defined. Seismic stratigraphic interpretation of shallow reflectors has led to the notion of a

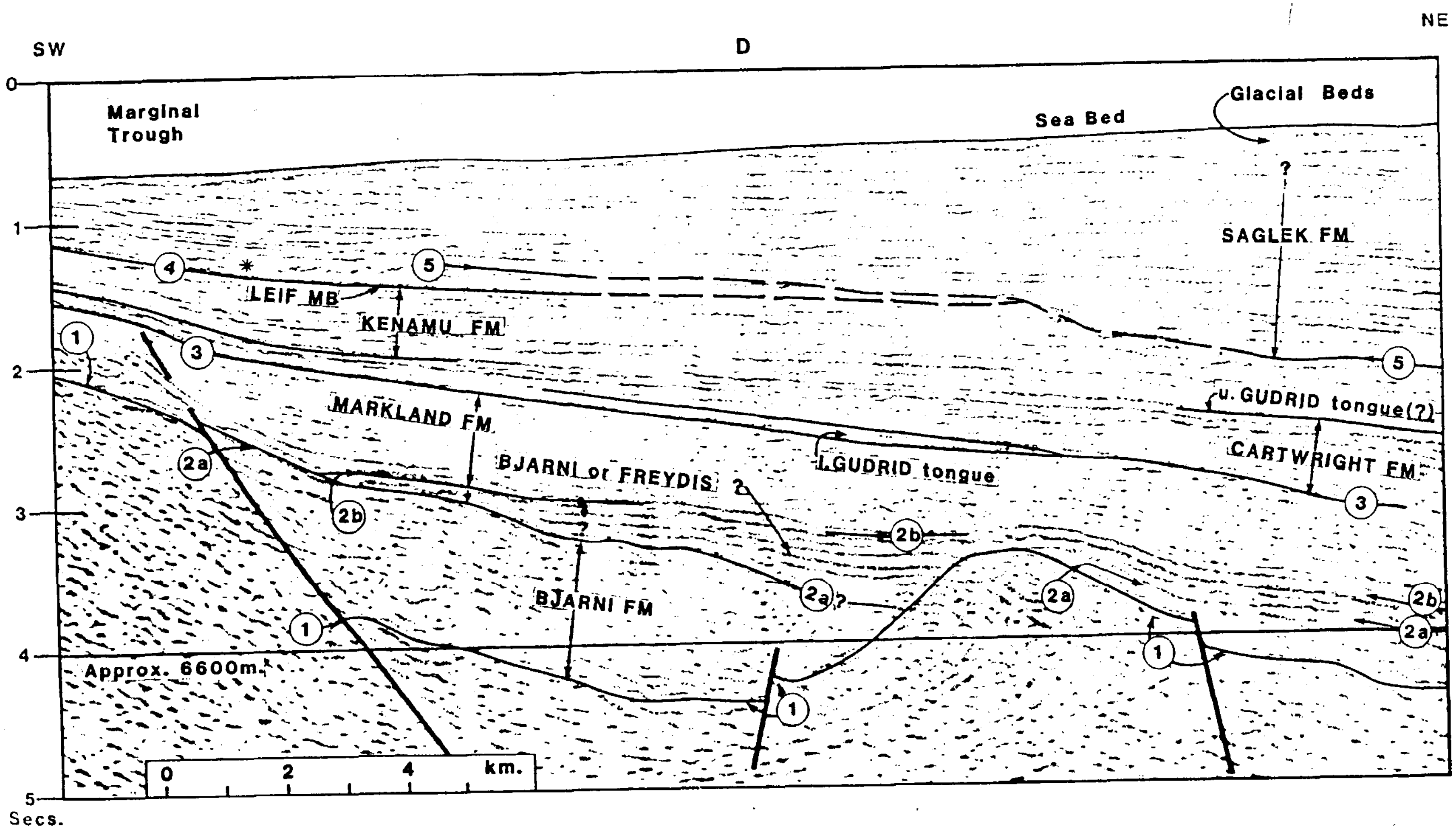


Figure 39. SEISMIC SECTION THROUGH THE LABRADOR CONTINENTAL MARGIN

After McWhae et al. (1980)

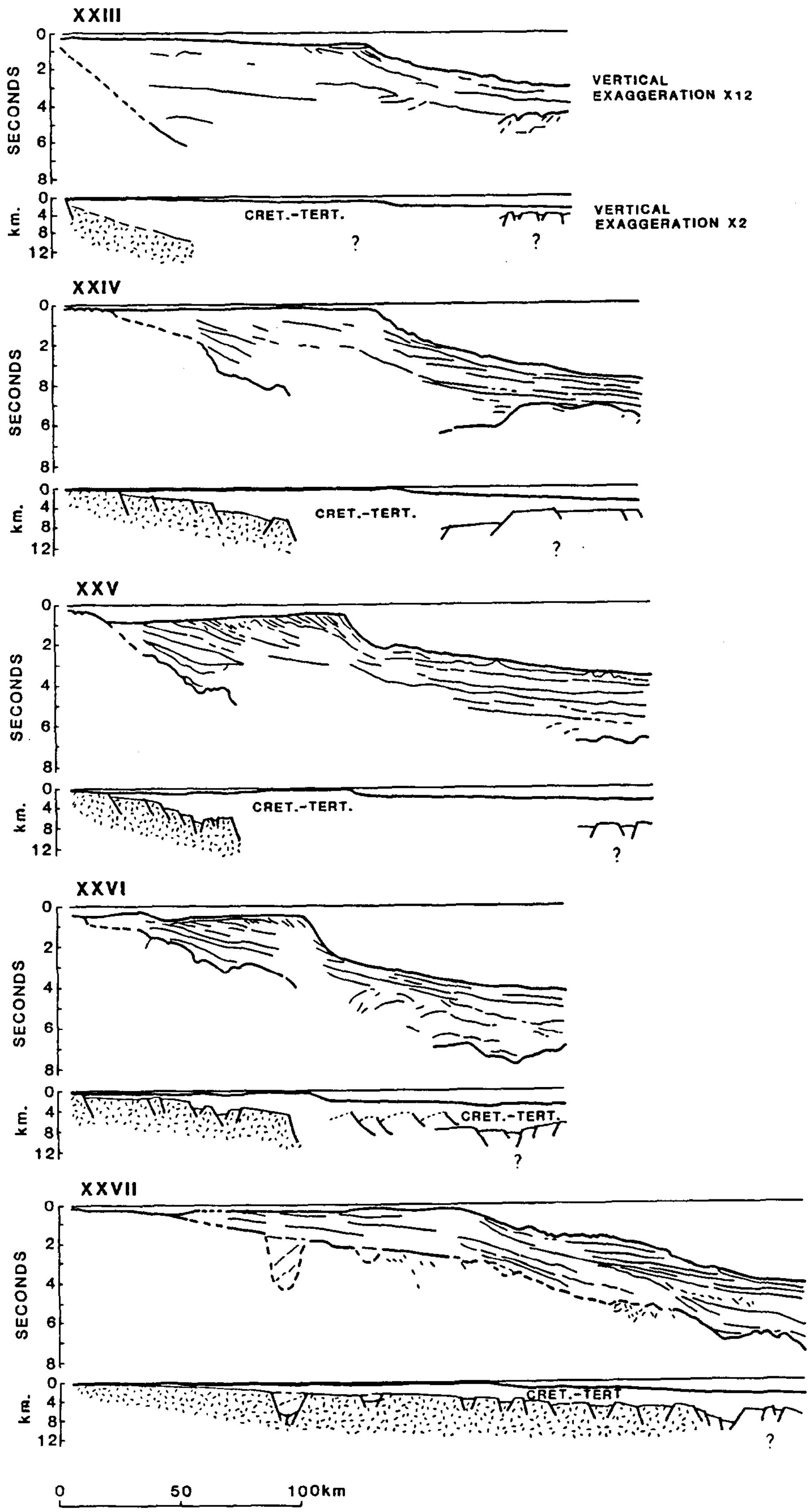


Figure 40. DIAGRAMMATIC SEISMIC PROFILES AND GEOLOGIC INTERPRETATION THROUGH THE LABRADOR CONTINENTAL MARGIN

Modified after Grant (1975)

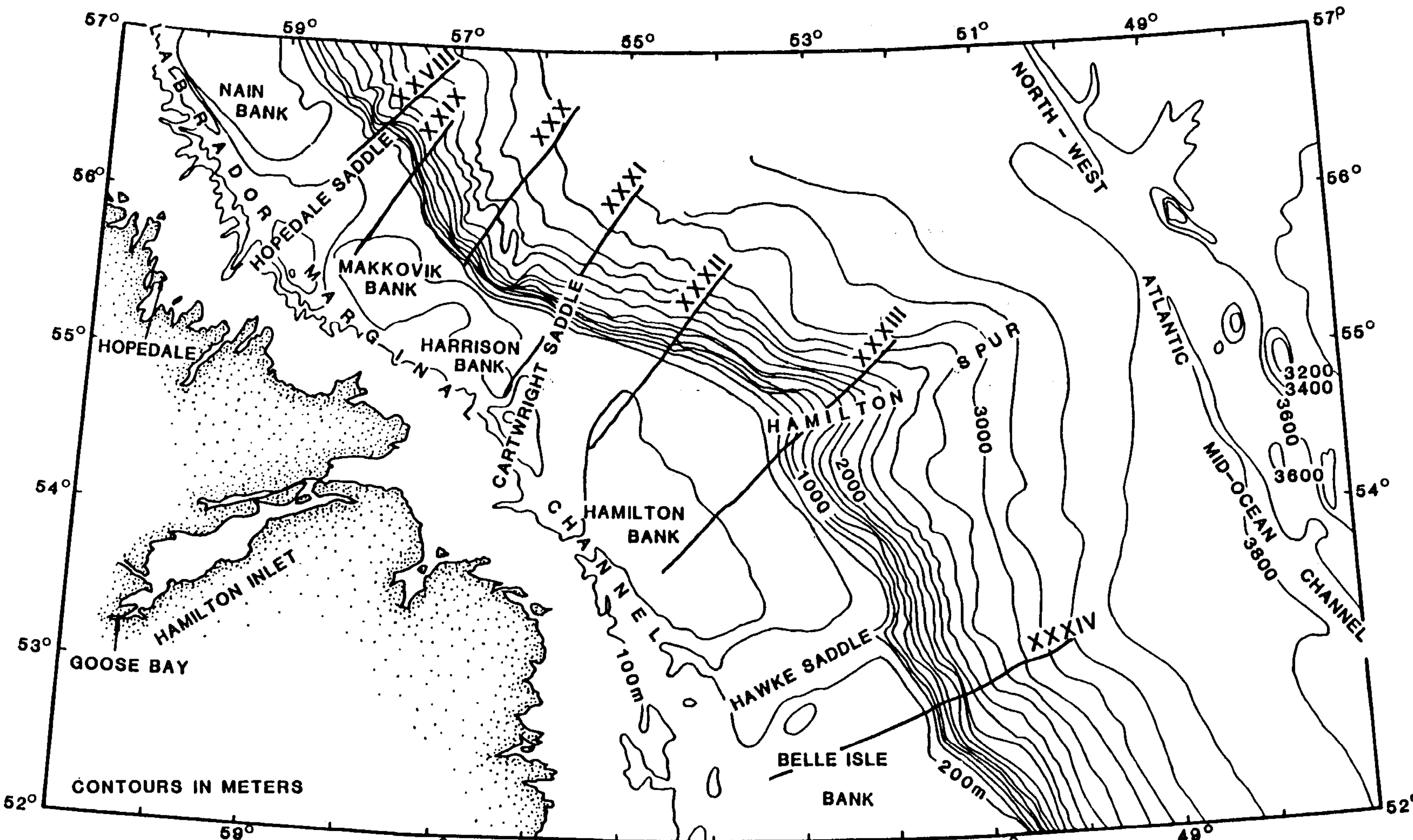
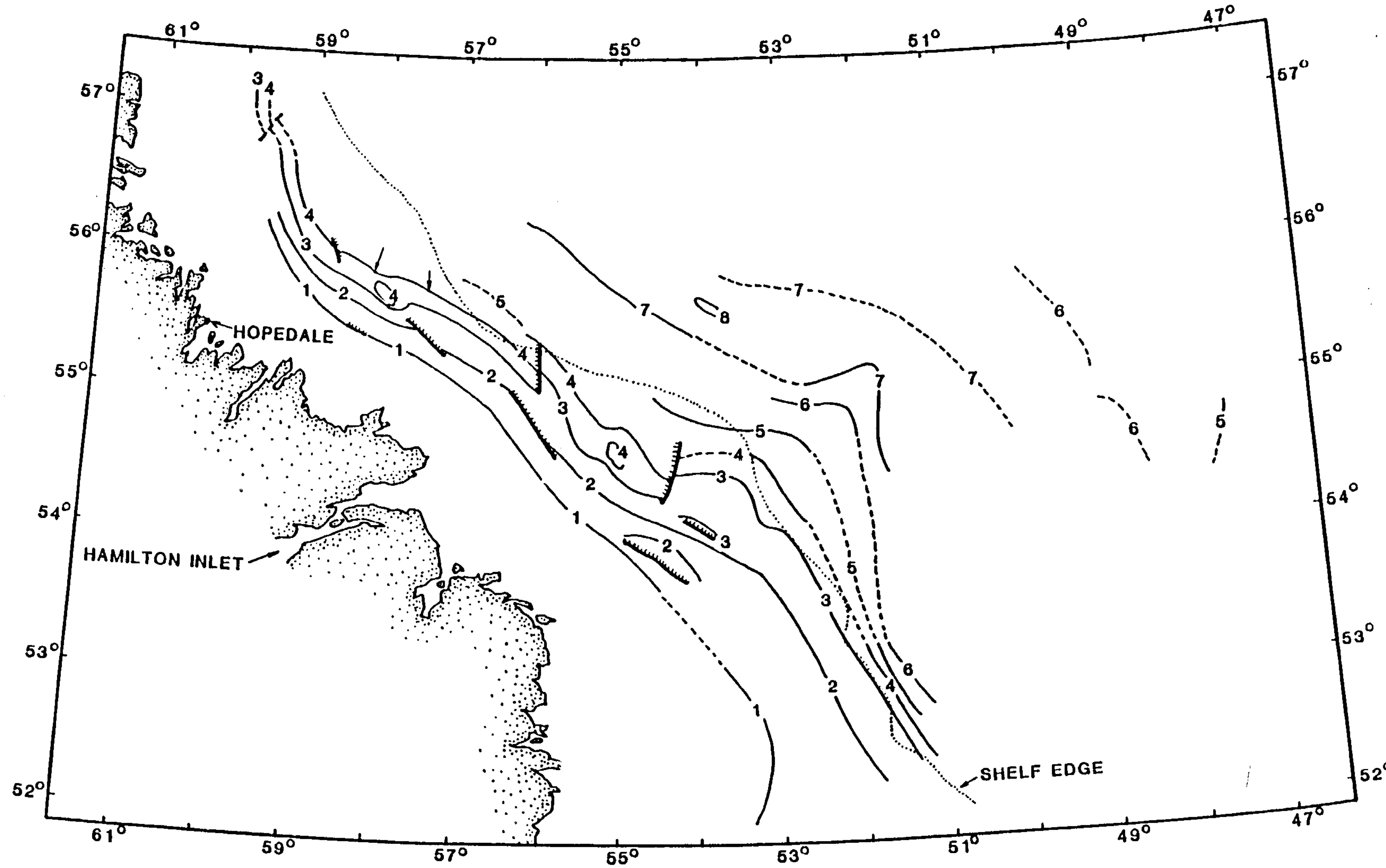


Figure 41. BATHYMETRIC MAP OF THE SOUTHERN LABRADOR CONTINENTAL MARGIN WITH LOCATION OF DIAGRAMMATIC SEISMIC PROFILES XXVIII THROUGH XXXVII

Modified after van der Linden and Srivastava (1975)



CONTOUR INTERVALS IN SEC. (TWO WAY TRAVEL TIME)

FAULT (BARBS ON DOWNTHROWN SIDE)

Figure 42. DEPTH TO ACOUSTIC BASEMENT MAP OF THE CENTRAL - SOUTHERN LABRADOR CONTINENTAL MARGIN

Modified after van der Linden and Srivastava (1975)

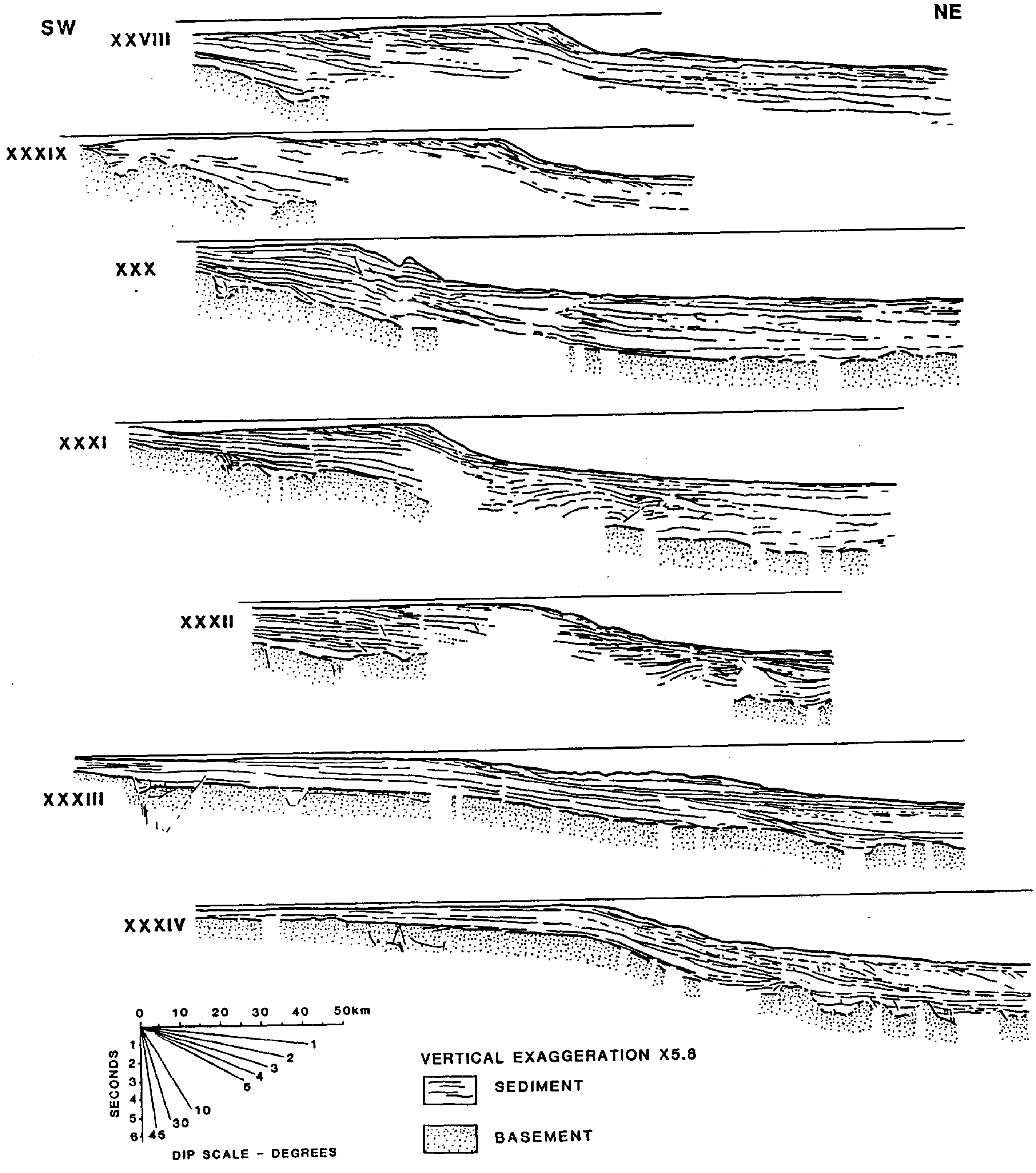


Figure 43. **DIAGRAMMATIC SEISMIC PROFILES THROUGH THE SOUTHERN LABRADOR CONTINENTAL SLOPE**

Modified after van der Linden and Srivastava (1975)

late Miocene erosional surface, successively overlain by prograding sediment wedges.

Quaternary. The impact of the Pleistocene glaciation is much more pronounced on the Labrador Shelf than along the Atlantic seaboard at lower latitudes. It is a prime example of a glaciated shelf (Grant, 1972; van der Linden, 1974; McMillan, 1973). The Pleistocene glacial deposits rest on a truncated, seismically distinct unconformity (Figure 44). The shelf is characterized by the widespread occurrence of a rather thick (commonly a few hundred meters) glacial drift. The overall erosional and depositional patterns of the Labrador Shelf are evidence for the large-scale, continental glaciation which affected the shelf during Pleistocene time. Major glacial features are:

- the presence of ice carved transverse channels some 50 km offshore (paleo-glacial valleys; Figure 41),

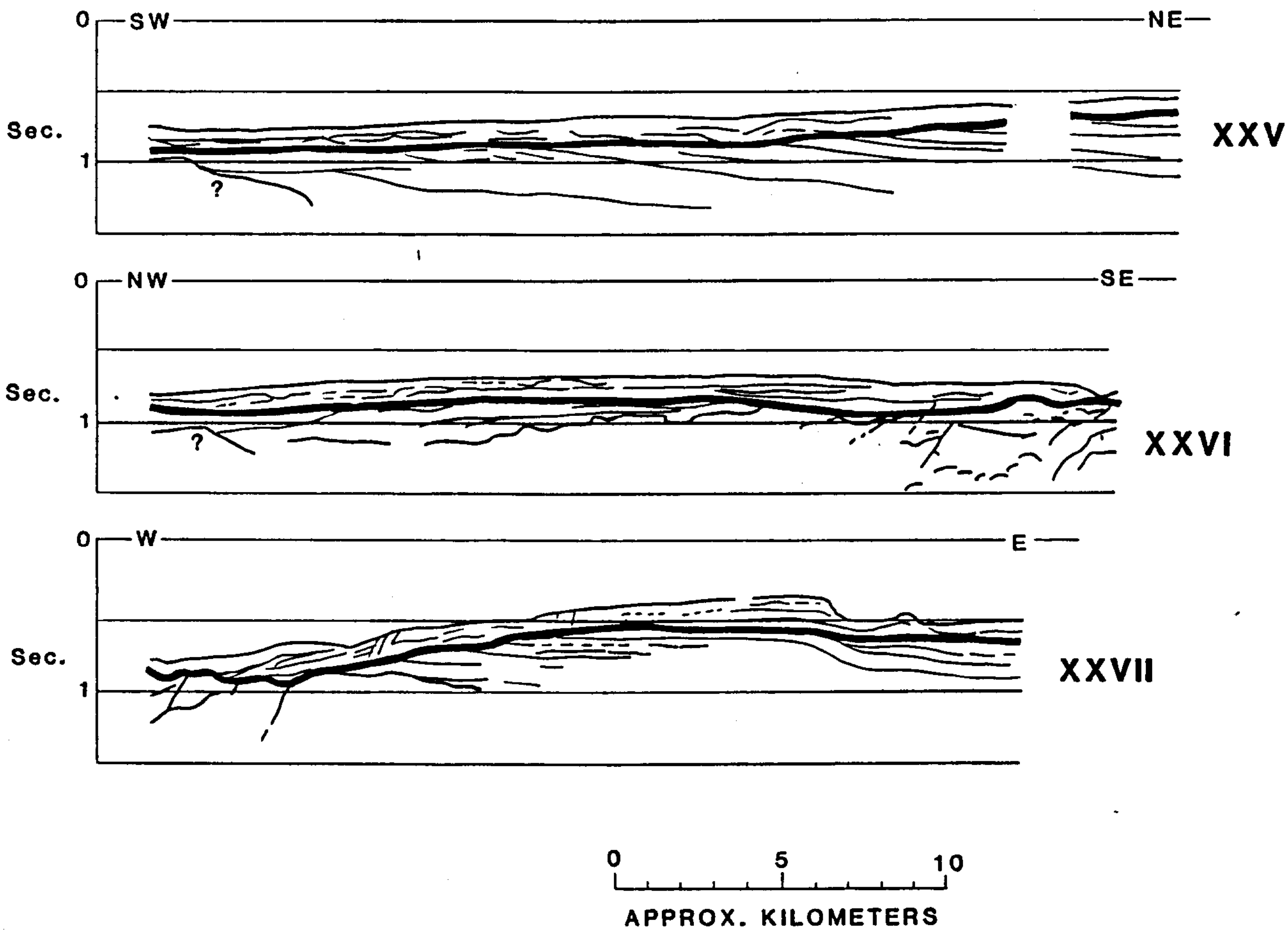
- the seaward occurrence of thick glacial drift material at the mouth of these channels,

- the erosional longitudinal channel which occurs all along the shelf at the contact between basement rocks and the sedimentary cover. This feature, thought to have developed by differential glacial erosion process, is known as the Labrador Marginal Trough and is presently filled with relict morainal material.

In detail, the repeated alternation of erosional and depositional cycles led to an extremely complex sedimentary pattern and the widespread occurrence of relict tills, outwash deposits, and marine reworked and redistributed glacial drift. The thick accumulation of unconsolidated sediment seaward from the transverse channels suggests that much material has been funnelled by glaciers to the outer shelf.

Superficially, the channel areas located between the banks are floored by well sorted, silty clays and fine grained sediments which appear to constitute a thin veneer (10 m average) resting over poorly sorted glacial drift (van der Linden, 1974). The surface of the banks is likewise draped by a sedimentary veneer of poorly sorted mud and gravel. The periphery of the banks offers the unusual situation of relatively fine sediments on their top in shallower water where the winnowing effect of the Labrador current is more pronounced, grading to coarse pebbly, poorly sorted to unsorted material on the flanks and seaward into deeper waters. Recent glacial sea floor scouring by icebergs is a common feature.

Overall, the Pleistocene was a period of outbuilding of the shelf and progradation of the shelf edge and concomitant mass transport and resedimentation at the slope. The late Tertiary pattern of mass transfer toward the Labrador Sea deep basin continued unabated during the Pleistocene. Slump scars along the present continental slope indicate that these young sediments have not yet been stabilized and are in a transient state. The clastic wedge deposited across the shelf edge, outer shelf zone during the late Pliocene - Pleistocene interval has a markedly triangular cross section with proximal parts as little as 300 m thick versus sediment thicknesses in excess of 1,500 m for the far outer shelf.



NOTE: ANGULAR UNCONFORMITY BETWEEN PLEISTOCENE AND PRE-PLEISTOCENE UNITS UNDERLINED

Figure 44. SHALLOW SEISMIC PROFILES FROM SOUTH LABRADOR SHELF (CARTWRIGHT SADDLE)

Modified after Vilks et al. (1974)

The Labrador Sea. The continental shelf quickly gives way seaward to the continental slope and the basin area of the Labrador Sea (Labrador Basin), which is more than 3,500 m deep in its central part (Figures 45 and 46).

A large body of recent information (mostly of speculative nature) deals with the opening (rifting) of the Labrador Sea and its presumed evolution (Grant, 1975; Gradstein and Srivastava, 1980; Hyndman, 1973; Hyndman et al., 1973; Laughton, 1971, 1972; Le Pichon et al., 1971; van der Linden, 1975a, 1975b; Srivastava, 1978; Srivastava et al., 1981; and others). Most of the hard geologic data used for this short discussion derives from the seismic stratigraphy interpretation presented by Hinz et al. (1979) and from two shallow DSDP drill sites (Sites 112 and 113, Laughton et al., 1972).

The outstanding feature of the Labrador Basin is a wedge of sediment from 1,500 m to 6,000 m thick under the continental slope, approximatively 5,000 m thick beneath the basin axis transferred from the shelf edge toward the continental rise and the bathyal domain during the late Tertiary and Quaternary. The importance of and the large volume of clastic material involved in this multiple resedimentation process should be emphasized.

In the slope area, the sedimentary package is seismically divided into two groups separated by a pronounced reflector interpreted as an unconformity (Figure 47). This seismic event can be traced with reasonable assurance to the late Miocene seismic unconformity beneath the shelf. This main reflector separates an onlapping sequence resting on truncated, sloping reflectors. The interpretation of the seismic sequence above the unconformity is less controversial and corresponds to the late Tertiary (Miocene - Pliocene) increase in clastic deposition on the shelf. This sequence can be divided into two groups. The lower one displays at its top hummocky and chaotic reflection patterns interpreted as being indicative of mass transport sedimentary processes (large scale slumps, slides, debris flows, and thick turbidite sequences). The upper seismic unit immediately below the sea bottom displays a progradational seismic pattern interpreted as the distal part of a landward thickening, aggradational clastic sequence.

The central part of the Labrador Sea is the site of a faulted acoustic basement overlain by a thick sedimentary section which is contorted in its lower part. The so called Central Rift Valley was tested in 1970 (DSDP Site 113; Laughton et al., 1970, 1972b) in the mid-southern Labrador Sea at 3,600 m of water. The penetrated section (925 m thick) is composed of late Miocene - Pliocene laminated mudstones, mudstone breccias with reworked Eocene and Oligocene pelagic sediments, fine grained turbidite sands, followed in the late Pliocene - Pleistocene by distal turbidites (silty, clay sequence) and ice rafted material.

The basement of presumably oceanic nature was not reached. The DSDP Site 112 (Laughton et al. 1970, 1972a) was drilled in the middle of the northwestern Atlantic Ocean, penetrating 660 m of sediment. Pelagic, nannofossil clays and marls, burrowed and mottled in the lower section, were recovered, resting on a basaltic substratum. This sequence of Paleocene to the early Pliocene age is overlain by Pliocene and Pleistocene silty muddy clays and ice rafted pebbles interbedded with hemipelagic silty clays and marls.

Petroleum Geology

Thirty-three oil and gas wells have been drilled in offshore Labrador since 1971; gas and hydrocarbon condensates have been discovered in five

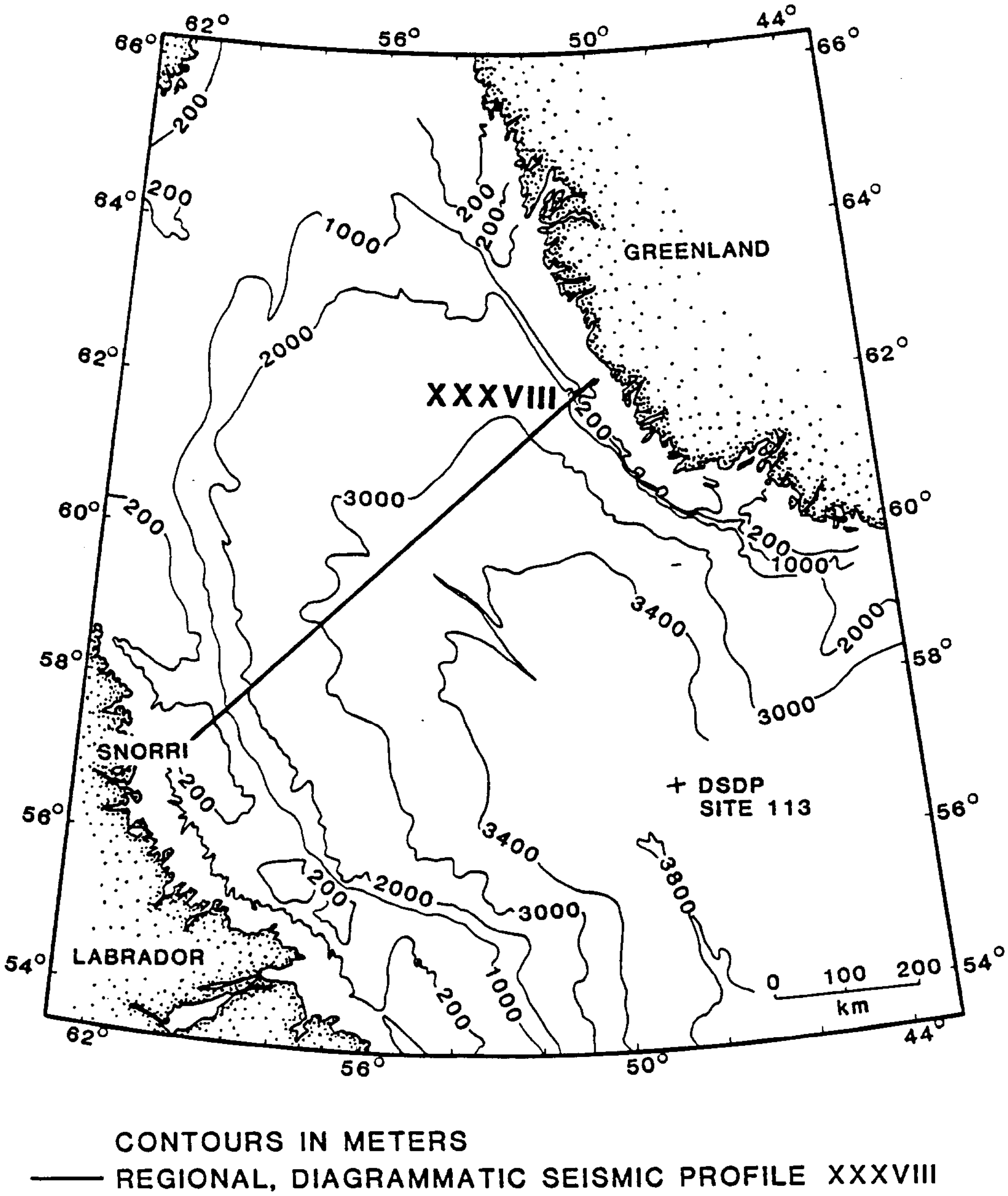


Figure 45. GENERALIZED BATHYMETRIC MAP OF THE LABRADOR SEA WITH LOCATION OF GENERAL AND DETAILED SEISMIC PROFILES

Modified after Hinz et al. (1979)

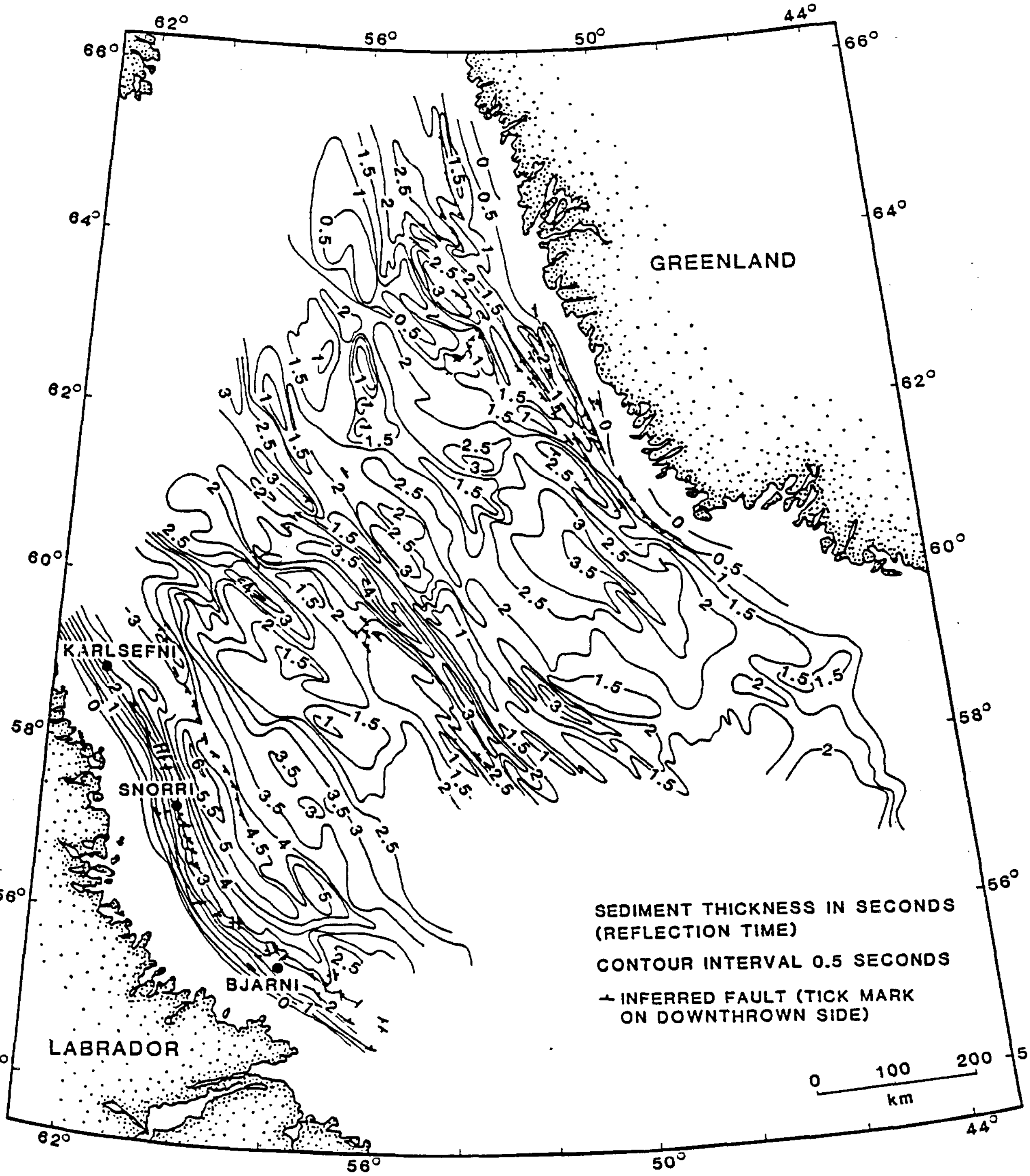
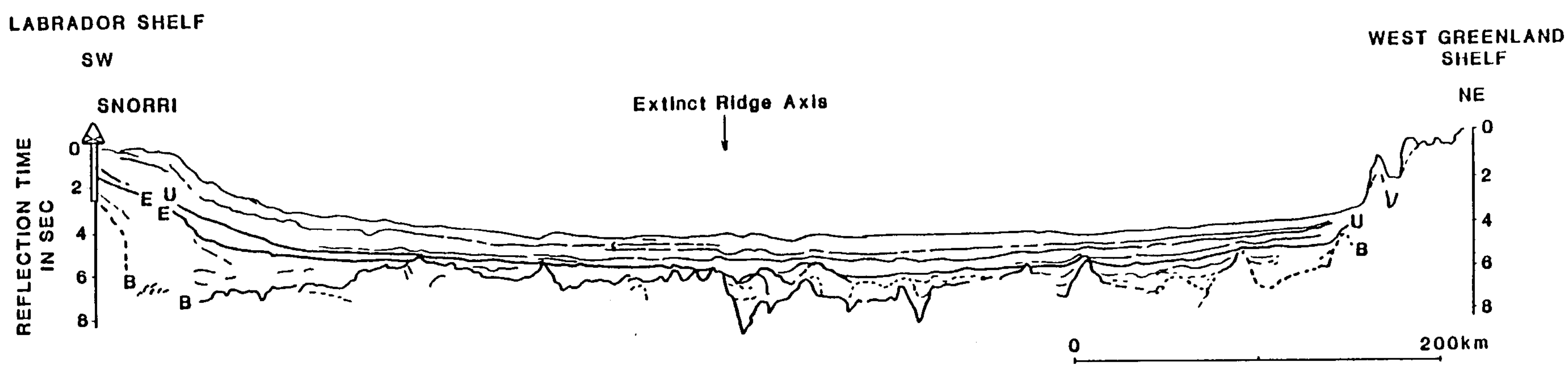


Figure 46. LABRADOR SEA MAP OF REFLECTION TIME INTERVAL BETWEEN SEA FLOOR AND ACOUSTIC BASEMENT (TOTAL SEDIMENT THICKNESS)

Modified after Hinz et al. (1979)

XLVI



LEGEND

U - LATE MIOCENE UNCONFORMITY
E - TOP EOCENE REFLECTOR
B - TOP ACOUSTIC BASEMENT

Figure 47. **REGIONAL DIAGRAMMATIC SEISMIC PROFILE THROUGH THE LABRADOR SEA**

Modified after Hinz et al. (1979)

wells in the southern basin (Hopedale Basin) in Paleozoic dolomites, Early Cretaceous sandstones onlapping basement blocks, and Tertiary sandstones atop basement structures. No economic discovery has been reported (Procter et al., 1983; Trevail et al., 1984).

A generalized tectonic pattern of the Labrador Shelf, similar to the Grand Banks and the East Newfoundland Basin is characterized by a middle Early Cretaceous rifting phase, which led to widespread crustal fragmentation (Figure 40). This period of block-faulting activity was followed by tectonic quiescence and passive subsidence from the early late Cretaceous onward. A regional unconformity broadly coeval with the Avalon Unconformity separates the two pre-rift and post-rift sedimentary mega sequences (Figures 38 - 40). At a smaller scale, tilted sub-unconformity blocks, faulted compartments draping over basement highs are common features. Good although uneconomic gas shows have been encountered by drilling over some of these structures (McWhae et al., 1980; Umpleby, 1979). Growth faulting along the present slope and the previous paleoslopes has affected the Cenozoic section (Grant, 1975; Hinz et al., 1979; Umpleby, 1979) and should provide conditions favorable for hydrocarbon entrapment. Also shale diapirism affecting geopressurized, distally deposited Eocene mudstones occurs locally along the present day continental rise. Their emplacement is inferred to have been a Miocene event.

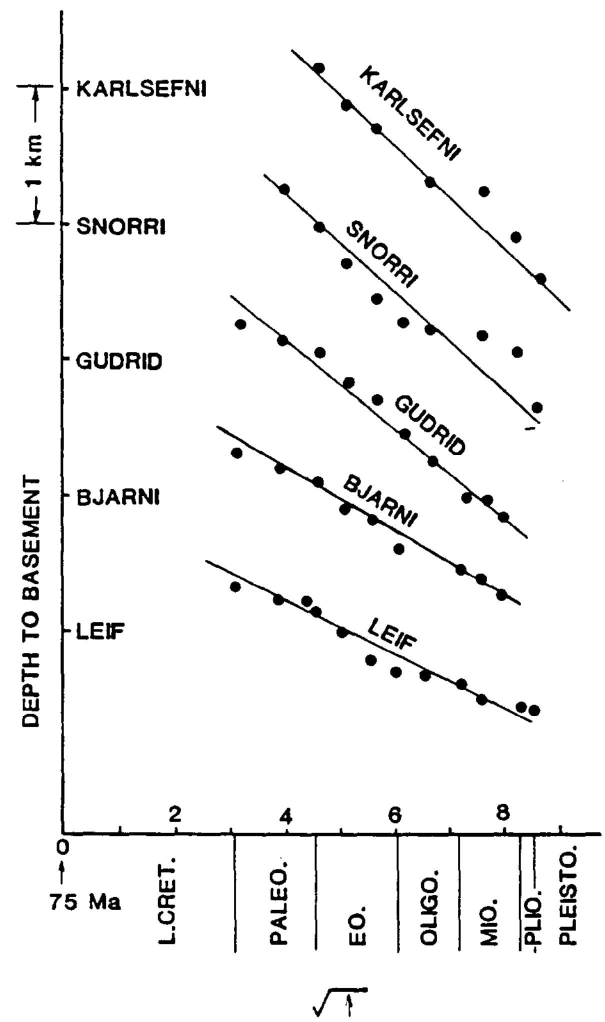
Subsidence and Thermal Evolution

More advanced subsidence analysis (Keen, 1979) clearly indicates the thermal nature of the tectonic subsidence of the Labrador continental margin. The corrected tectonic subsidence computed from 5 wells does not display any significant deviation from the linear $t^{\frac{1}{2}}$ relationship (Figures 48 - 50). This observation is attributed to the fact that the Labrador Shelf is a young continental margin which underwent initial breakup in the early Cretaceous and consequently still is at an early stage of evolution.

Subsidence curves have been used by Royden and Keen (1980) to compute the paleoheat flow and temperature distribution within the sedimentary pile of the margin at a given time. This procedure is based on a passive, conductive, cooling lithospheric model after crustal rifting (Figures 51 and 52). The paleotemperature estimates suggest that thermal conditions have been favorable for hydrocarbon generation in some of the older strata. The paleoheat flow modeling also indicates subcrustal thinning of the continental margin in accordance with seismic refraction measurements (20,000 m average thickness).

Discussion

Labrador Shelf. Thermogenic and biogenic gases have been documented from the Labrador Shelf. Several major gas shows with varying amounts of condensates have been recorded on the Labrador Shelf (Powell, 1979; Purcell et al., 1980; Rashid et al., 1980; Figures 53 - 56). These gas shows occur in lower Paleozoic dolomites, Lower Cretaceous basement onlap sandstones and Tertiary sandstones atop basement structures. Geochemical studies by Powell (1979) and Rashid et al. (1980) indicate that the hydrocarbons are derived from terrestrial organic matter which matured at deeper level in adjacent



TECTONIC SUBSIDENCE PLOTTED AGAINST THE SQUARE ROOT OF TIME SINCE 75 M.Y.

Figure 48. TECTONIC SUBSIDENCE CURVE FOR FIVE EXPLORATORY WELLS OFFSHORE LABRADOR

Modified after Keen (1979)

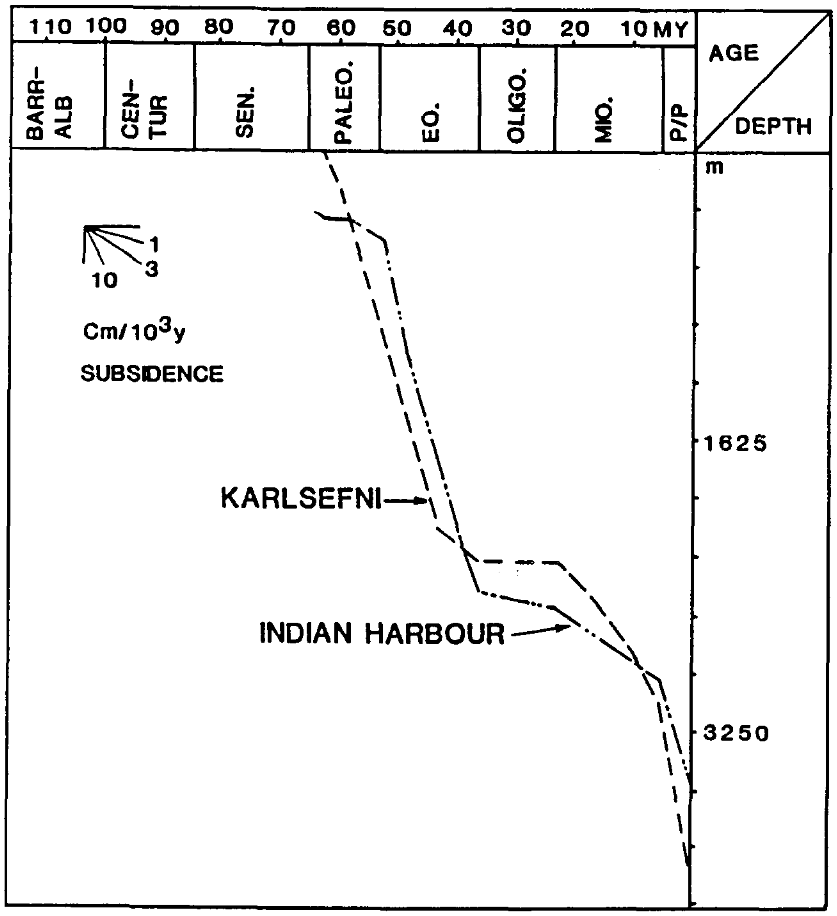


Figure 49. TOTAL SUBSIDENCE HISTORY FOR THE KARLSEFNI AND INDIAN HARBOUR EXPLORATORY WELLS (UNCORRECTED FOR COMPACTION)

Modified after Gradstein and Srivastava (1980)

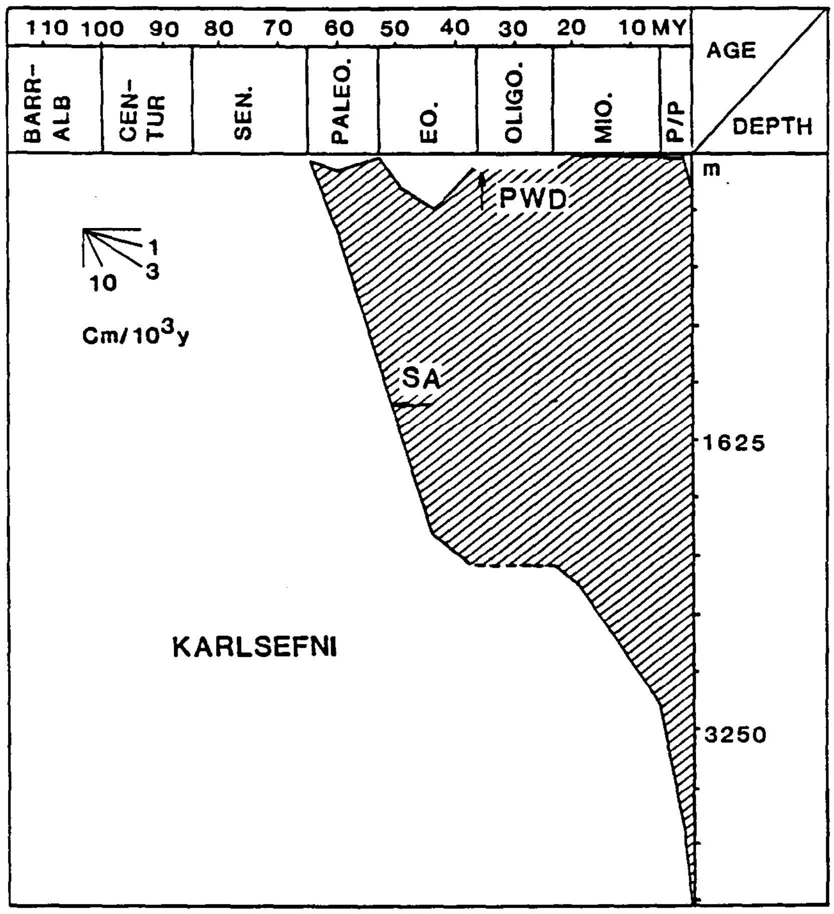


Figure 50. CUMULATIVE SEDIMENT ACCUMULATION (SA) PLOTTED AGAINST PALEOWATER DEPTH (PWD) THROUGH TIME FOR THE KARLSEFNI EXPLORATORY WELL

Modified after Gradstein and Srivastava (1980)

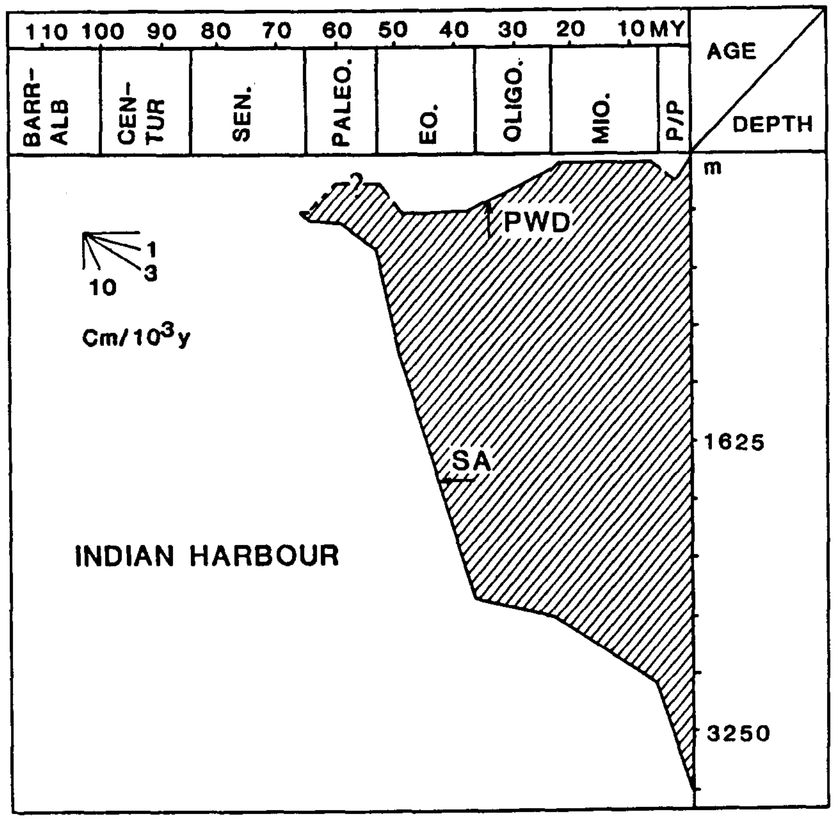
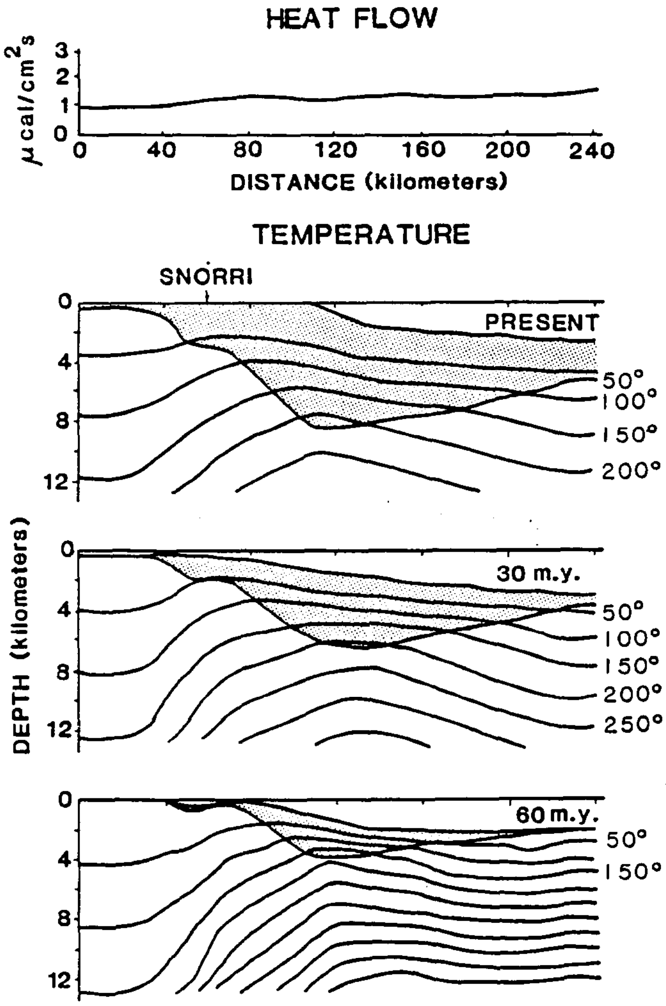


Figure 51. CUMULATIVE SEDIMENT ACCUMULATION (SA) PLOTTED AGAINST PALEOWATER DEPTH (PWD) THROUGH TIME FOR THE INDIAN HARBOUR EXPLORATORY WELL

Modified after Gradstein and Srivastava (1980)



SEDIMENTARY ROCKS SHADED
TEMPERATURE ISOTHERMS IN 50°C INTERVALS

Figure 52. PRESENT HEAT FLOW AND PRESENT AND PAST TEMPERATURE DISTRIBUTION ALONG A PROFILE THROUGH THE SNORRI EXPLORATORY WELL, LABRADOR CONTINENTAL MARGIN

Modified after Royden and Keen (1980)

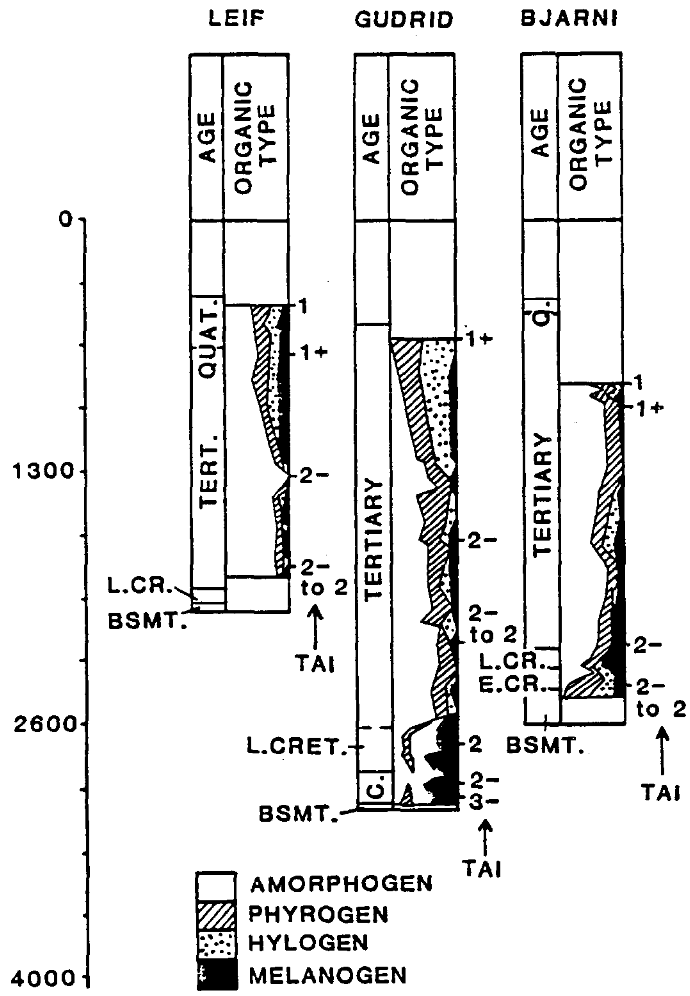


Figure 53. **ORGANIC MATTER TYPE AND THERMAL ALTERATION INDEX (TAI) FOR THREE EXPLORATORY WELLS FROM THE LABRADOR CONTINENTAL MARGIN**

After Bujak et al. (1977)

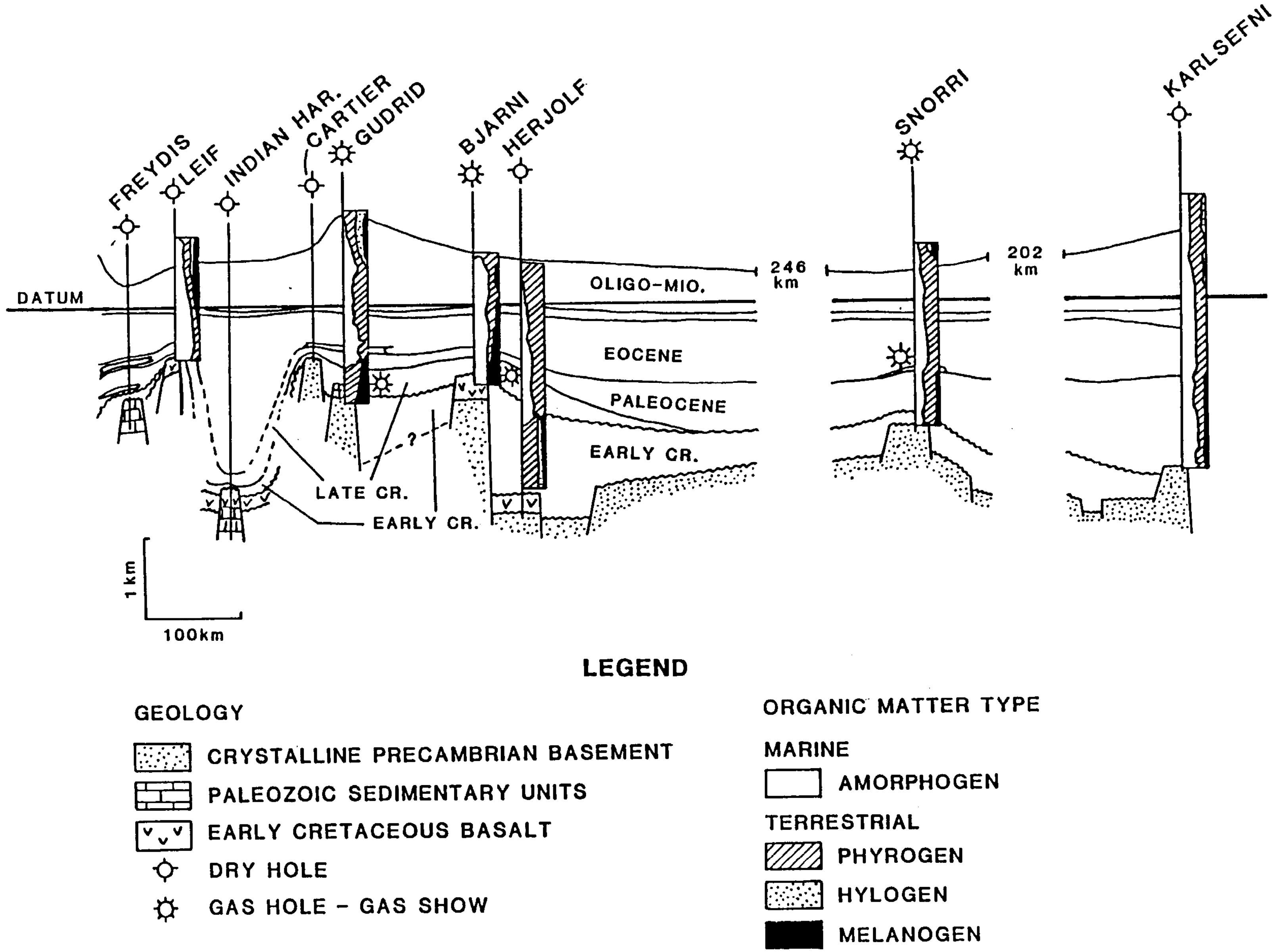


Figure 54. **DIAGRAMMATIC STRATIGRAPHIC CROSS-SECTION AND DISTRIBUTION OF ORGANIC MATTER TYPE THROUGH THE LABRADOR SHELF**

Modified after Rashid et al. (1980)

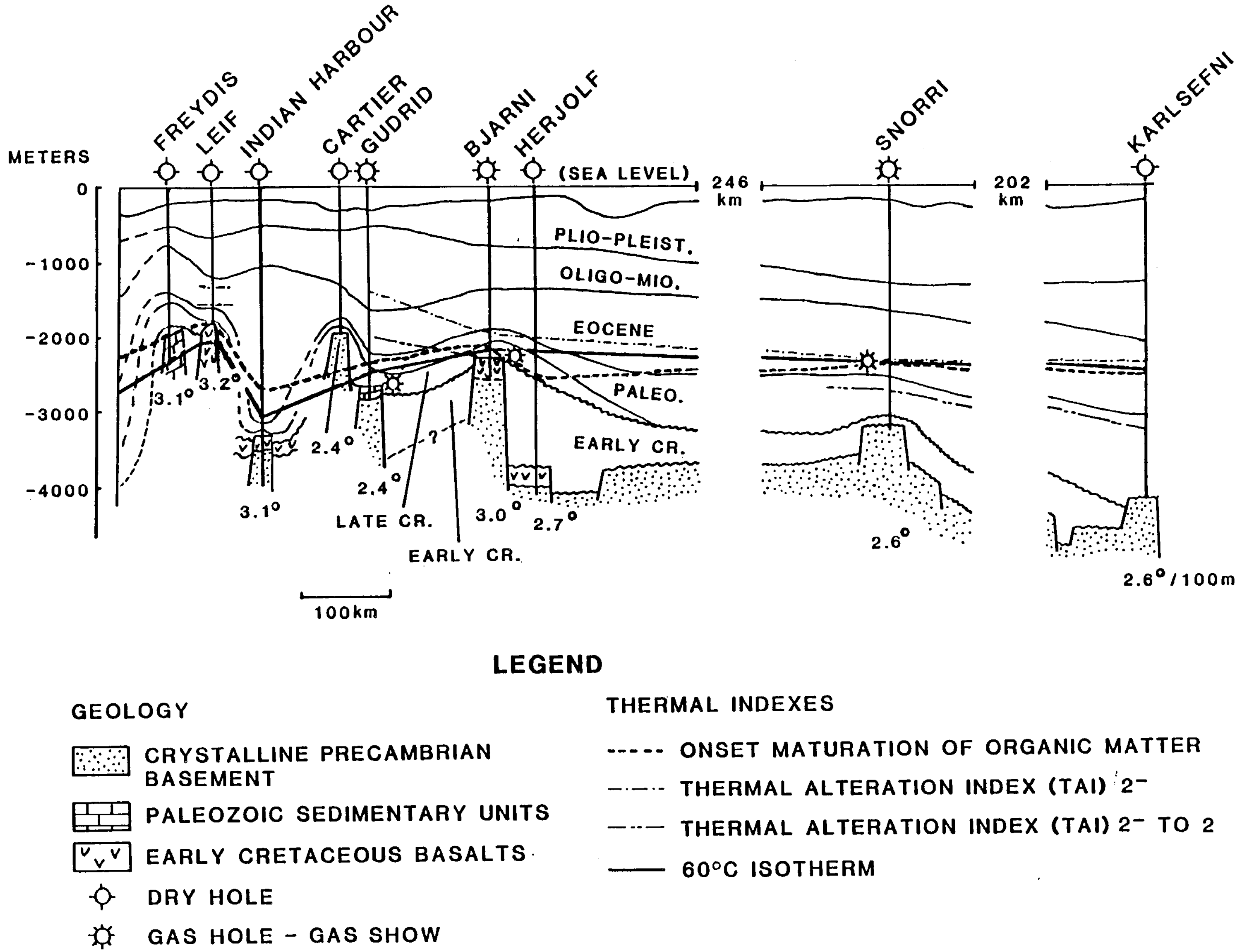


Figure 55. THERMAL MATURATION INDEXES - LABRADOR SHELF

Modified after Rashid et al. (1980)

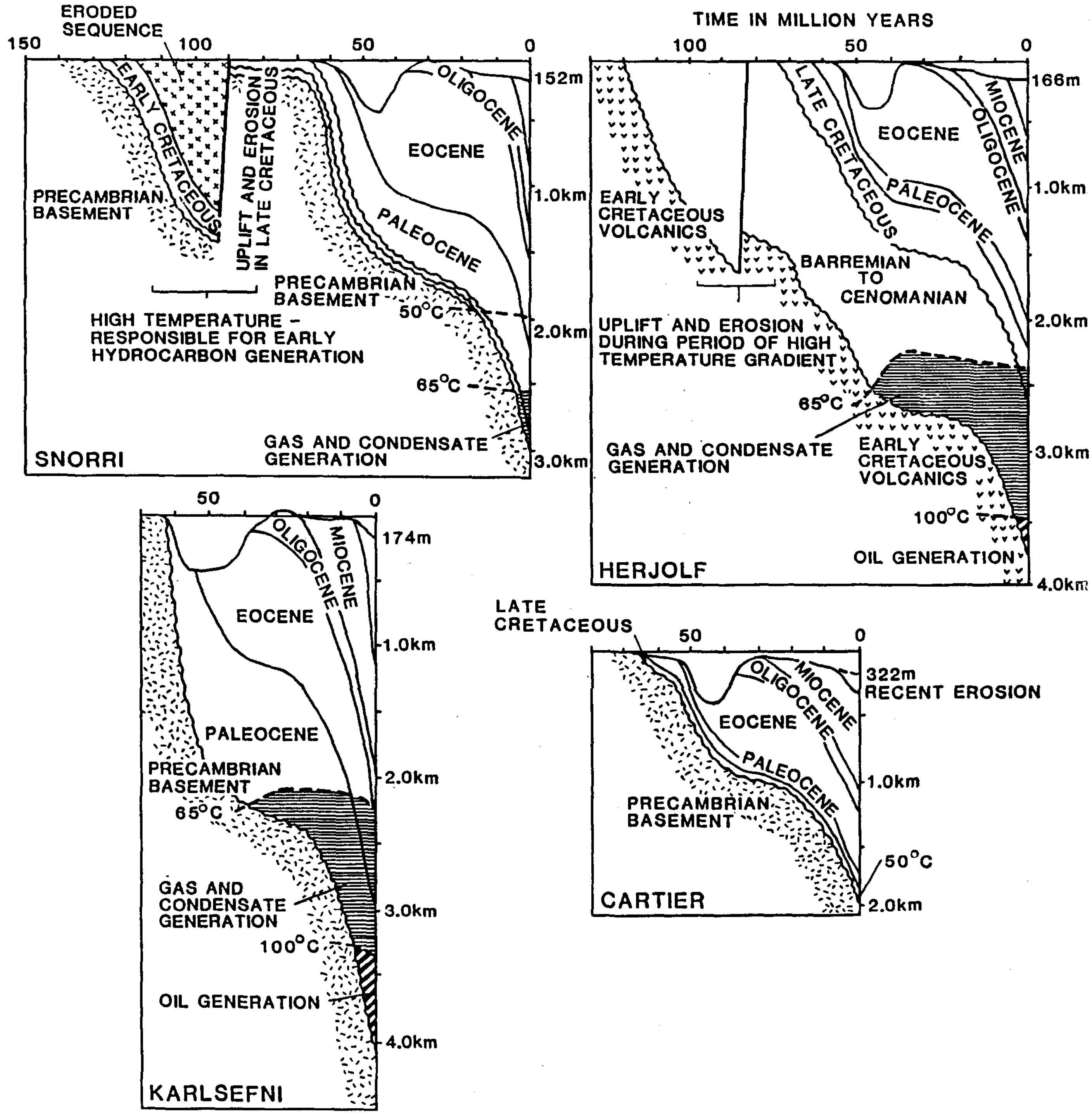


Figure 56. SUBSIDENCE CURVES, COMPACTION AND THERMAL HISTORIES OF FOUR EXPLORATORY WELLS FROM THE LABRADOR SHELF

Modified after Umpleby (1979)

troughs and migrated upward into structural traps. Thermal organic matter maturation studies undertaken by Cassou et al., (1977) confirm that the deep part of the sedimentary prism reached the oil generating window (Figure 53).

The presence of thermogenic gas is firmly documented and the possibility of natural gas trapped under a gas hydrate seal cannot be discounted. However, there is no direct evidence for the presence of gas hydrates.

More importantly, biogenic methane occurrences are known from the Pleistocene transverse channels (Vilks et al., 1974; Rashid and Vilks, 1977; and Vilks and Rashid, 1977) of the southern part of the shelf (Figures 41 - 49). Pure methane, up to 16,000 ppm, has been found in superficial unconsolidated muds lying at the bottom of Pleistocene depressions (Figure 54). They are part of a recessional moraine sequence reworked by an encroaching sea. Such sediments were deposited during the last glacial retreat in a previously ice carved channel. The thickness of the mud cored intersects can not be determined. Shallow seismic profiles show shallow dipping reflectors within the glacial drift cover, which is itself no thicker than 200 m. The inference is that the muddy units cannot be more than a few meters thick. The lateral extention of these mud bodies, which occur in poorly sorted marine reworked glacial outwash deposits is limited.

According to Vilks et al. (1974), a number of sediment cores were taken from two enclosed, superficial depressions on the continental shelf off southern Labrador, during the 1973 field season. The sediments were taken with a piston corer. Within minutes of recovery, the black muds began to release gas that caused the formation of transverse fissures in the core. These fissures gradually expanded while some of the sediment was forced out through the ends of the plastic liners. The volume increase of the sediment resulting from the release of the gas was estimated up to 10% in the bottom sections of the cores. Maximum core recovery ranged between 10 to 12 m and approximatively the top 3 m of the sediment did not release gas. Gas chromatography showed that the gas was pure methane suggesting generation by anaerobic bacterial fermentation. The total organic carbon of the sediments is surprisingly low (0.3 to 0.5%). This suggests that the oxidation-reduction status of a sediment may be more important in methanogenesis than the total organic matter content. The muds were deficient in interstitial oxygen but were not totally anoxic. Another possibility is lateral or vertical migration of the biogenic methane from sediments with higher organic carbon contents.

In a general article reviewing potential drilling risk and offshore hydrocarbon production from the east coast of Canada, Taylor et al. (1979) speculated about the applicability of gas hydrate theoretical pressure - temperature stability relationships with respect to conditions prevailing in the Labrador Shelf. Gas hydrates are not stable below shallow water because of insufficient pressure and consequently cannot be expected to occur under present day conditions of the Labrador Shelf. However, Taylor et al. (1979) theorized about the possible existence of relict gas hydrate zones of Pleistocene age. The overburden of continental glacier ice was enough to have brought the sea floor sediments within the pressure stability range of gas hydrates. Taylor and his coauthors imply that the present methane shows from the top sediments may be related to the degassing of relict gas hydrate zones in the process of degradation. Some piston core samples collected by Vilks (pers. commun., in Taylor et al., 1979), in a few hundred meters of water depth, exhibited extrusion of sediment from the core barrel, when brought to sea level, in a manner similar to that observed from deep sea cores collected from suspected gas hydrate zones. It is not clear if their cores are the same as those described above.

Labrador Sea. Data pertinent to the assessment of the gas hydrate potential in the Labrador Sea are sparse. No BSRs have been reported in the literature from seismic profiles. The thermal evolution of the sedimentary sequence is purely speculative, and the influx of organic matter at the level of the continental slope is also a matter of conjecture. Considering the large extent of resedimentation processes which occurred along the slope and the bathyal domain, a significant component of terrestrial organic matter is to be expected, mixed with autochthonous planktonic input, but the overall bulk amount is inferred to be small (less than 0.5%). Data from DSDP Sites 112 and 113 do not permit a quantified assessment of the amount of organic matter within the core, the impression being of low values, based on the color description of the fresh core.

The color of freshly sampled marine sediments is a qualitative indicator of the oxidation-reduction history of a sediment during deposition and early diagenesis. A reducing, nonoxygenated pore environment leads to the preservation of organic matter, sulfate bacterial reduction, and formation of iron sulfides; consequently imparting a dark color to the sediment. Conversely, a well aerated medium leads to oxidation and degradation of the organic matter and oxidation of the iron bearing compounds and minerals and formation of iron hydroxides and oxides imparting a light to reddish color to the sediment. A complete transitional spectrum exists between the two extreme situations. On a practical basis, the color of a sediment can be taken as a good indication of its relative oxidation-reduction state and its amount of reactive, nondegraded organic matter.

<u>DSDP Site 112</u>. Although 660 m of mainly hemipelagic deposits were drilled to the basaltic basement at this site, the color descriptions imply an oxic depositional environment. In particular, reference to reddish and goethite-bearing lithologies indicate an environment unlikely to preserve organic matter.

The sediment flux rates are calculated as follows:

Pleistocene: 7.3 $mg/cm^2/yr$
Late Pliocene: 4 $mg/cm^2/yr$
Miocene: 3.2 $mg/cm^2/yr$
Oligocene: 2.4 $mg/cm^2/yr$
Eocene: 2.4 $mg/cm^2/yr$

These values are very low and sediment influx is not considered capable of producing anoxic sediment conditions. Also, Manheim et al. (1972) show that the interstitial pore fluids contain high concentrations of dissolved sulfate at depths to at least 380 m, consistent with a relatively oxidized, sediment surface environment throughout the Cenozoic.

<u>DSDP Site 113</u>. The mudstones and silty clays of Pliocene age, cored between 625 m and 920 m, have the most potential for bacterial methane generation, based on color descriptions. The abundance of dark brown to

black clays associated with visible pyrite clearly indicates a strongly reduced lithology. The Pleistocene and late Pliocene section appears to be more strongly oxidized.

The average sediment influx rates are calculated as follows:

Pleistocene: 16.2 $mg/cm^2/yr$
Late Pliocene: 57 $mg/cm^2/yr$

These rates are high for the deep water environment and are probably related to mudflow and turbidity activity. However, these sediments apparently were not accumulated with significant amounts of organic matter. Manheim et al. (1972) indicate high dissolved sulfate in pore fluids throughout the Cenozoic section. However, the reduced early Pliocene clays were not sampled.

The Pleistocene sedimentation for the Labrador Sea appears to be a rather uniform ice-rafted, current deposited, oxidized clastic assemblage, poor in organic matter of overall terrestrial derivation. This terrestrial organic matter is in all likelihood partly degraded and oxidized and consequently of limited generative capacity.

Seismic Evidence. A review of the public domain seismic profiles of the study region revealed one unreported BSR in the Labrador Basin. Seismic sections of the study region totalling 31,600 km have been made available by the U.S. Navy, Lamont-Doherty Geological Observatory (LDGO), Woods Hole Oceanographic Institution, and Scripps Institute of Oceanography. The profiles were inspected at the National Geophysical Data Center in a search for anomalous reflectors. The majority of the seismic sections did not have sufficient resolution or penetration to confirm or disprove the presence of BSRs. A very faint reflection which paralleled the sea floor at 0.53 seconds subbottom depth was located on a section collected on a cruise leg 71D of the USNS Lynch. The reflector was obtained at 0900 GMT at 53° 20' N, 47° 17' W in over 4,000 m water depth (Figure 57). The reflector was faint in the original positive microfilm, but it is considered to be a BSR with confidence due to its contour, depth, and conformable relationship to nearby reflectors. Copies obtained from the original record are of poor quality; interpreted and uninterpreted copies of the BSR are presented in Figure 58.

The geology of the deep Labrador Basin or Sea was investigated by DSDP Leg 11 (Laughton et al., 1972). The area is covered by thin accumulations of Tertiary sediments over oceanic crust. The area is underlain by extinct sea floor spreading centers which were active during the period of 60 to 47 m.y. The location of the proposed BSR is probably floored by crust about 60 m.y. old. Located just northeast of the BSR site is a ridge which Laughton interpreted to be the sea spreading center active when the North American and Greenland plates first separated. This center soon became dormant and spreading shifted to a new rift to the north. However, the dormant ridge remained a strongly positive topographic feature which directed subsequent sedimentation. Areas east of the ridge received sediments from the Norwegian Sea by bottom currents. West of the ridge, terrigenous input from North America dominated sedimentation. Although DSDP Site 112 was located much closer to the location of the possible BSR than was Site 113, Site 113 received terrigenous input from the west and thus should have sedimentary section more similar to that of the BSR location. Presumably the dark rocks with probable bacterial methane generation potential found at Site 113 may be present at the BSR site.

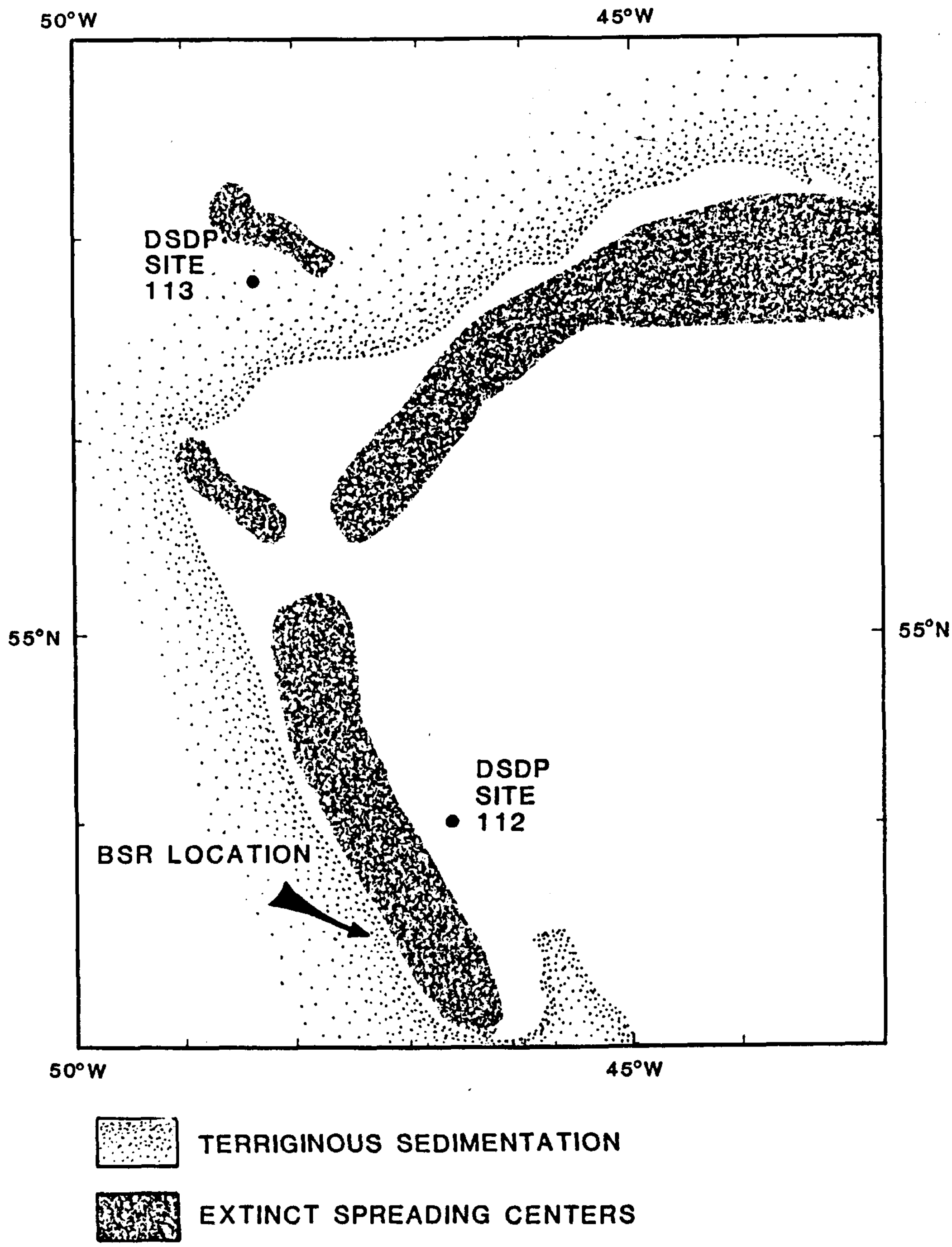


Figure 57. LOCATION AND SEDIMENT PROVENANCE OF POSSIBLE BSR

After Laughton (1972)

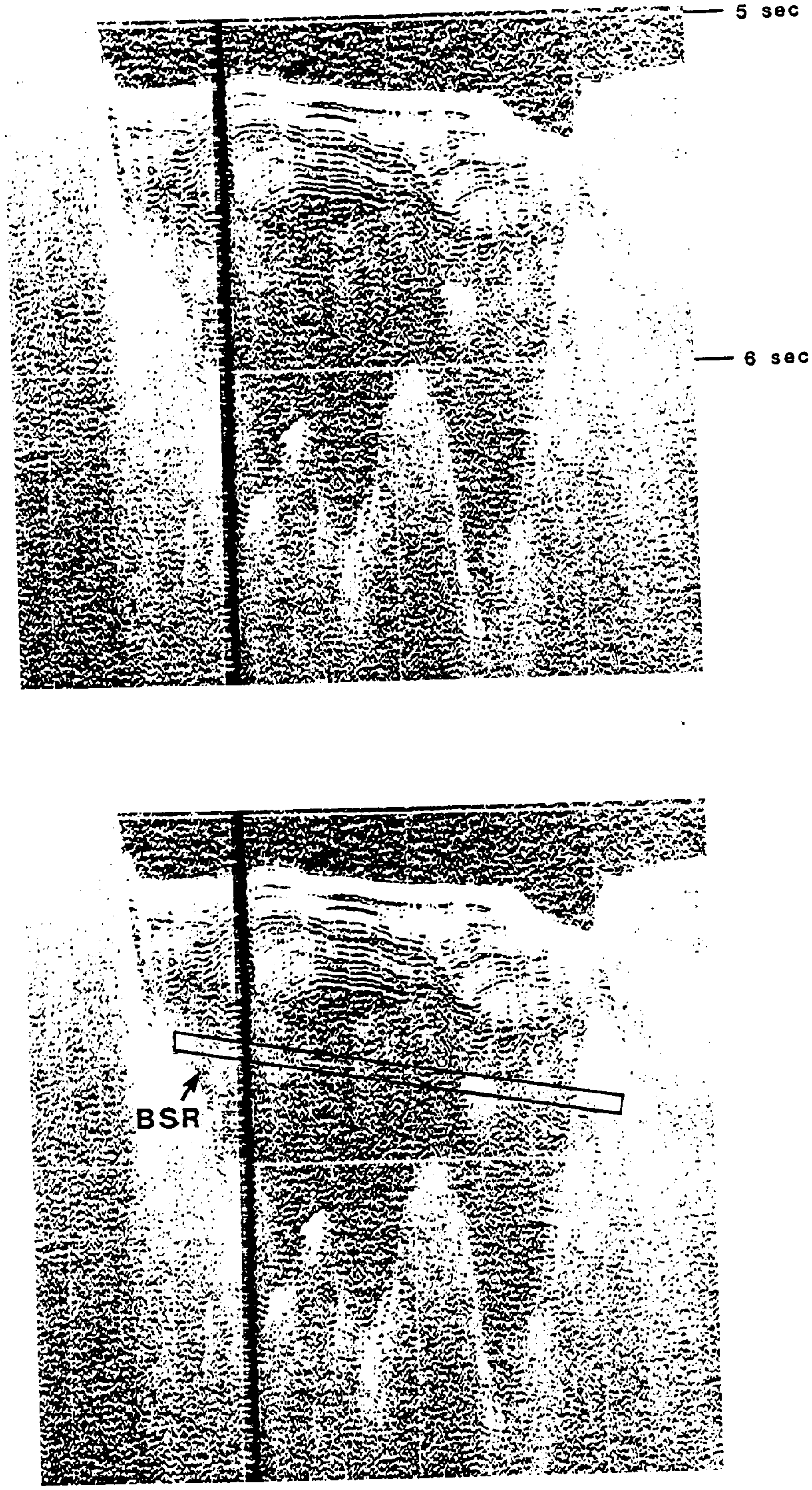


Figure 58. POSSIBLE BSR IN LABRADOR SEA
After U.S. Navy (1976)

PART II

GAS HYDRATE POTENTIAL

The designation of the Labrador Shelf and Northwestern Atlantic Ocean off Newfoundland as a potential gas hydrate site by DOE-METC is based upon the discussion of Taylor et al. (1979). These authors discuss the potential of hydrates as a hazard to potential drilling operations on the outer Labrador Shelf, but the presence of hydrates is conjectural. Also referenced are remarks by L.R. Kenard and R. Coffman (Imperial Oil) regarding the recognition of one BSR on a seismic profile north of Flemish Cap. This presumably is the information used by DOE to place the BSR water depth at 2,000 meters (6,600 feet) and consequently at the slope-rise transition region.

At this site, we are faced with a similar situation to the Baltimore Canyon Trough, i.e. a plethora of information for the shelf region where gas hydrates are unlikely to occur, and a paucity of information for the slope-rise regions where gas hydrates are most likely to be stabilized. We therefore base the gas hydrate potential on an examination of critical factors which may have stabilized gas hydrates in the slope and rise environment.

Sedimentary Environments

Shelf - Slope

In the area discussed by Taylor et al. (1979), are a number of Pleistocene sedimentary depressions trending approximately perpendicular to the coastline. They lie beneath the continental shelf and upper slope. Vilks et al. (1974) indicate that the topmost few meters of muddy sediment (post-Pleistocene) in these regions is highly gassy as a result of bacterial generation of methane (Figure 59). Therefore, at least surficially, these regions may have sufficient dissolved methane to promote hydrate growth. Vilks et al. (1974) note that the Quaternary deposits in these glacial depressions are 100 - 200 m thick and may include interbedded glacial muds and coarser clastics (Figure 48). The organic matter associated with the muds is probably marine because of the lack of Pleistocene land vegetation.

The pre-Pleistocene geology of the Labrador Shelf is a thick seaward dipping wedge of Mesozoic and Cenozoic strata which is the focus of petroleum exploration. Several major gas shows with various amounts of condensates have been encountered (Powell, 1979; Rashid et al., 1980).

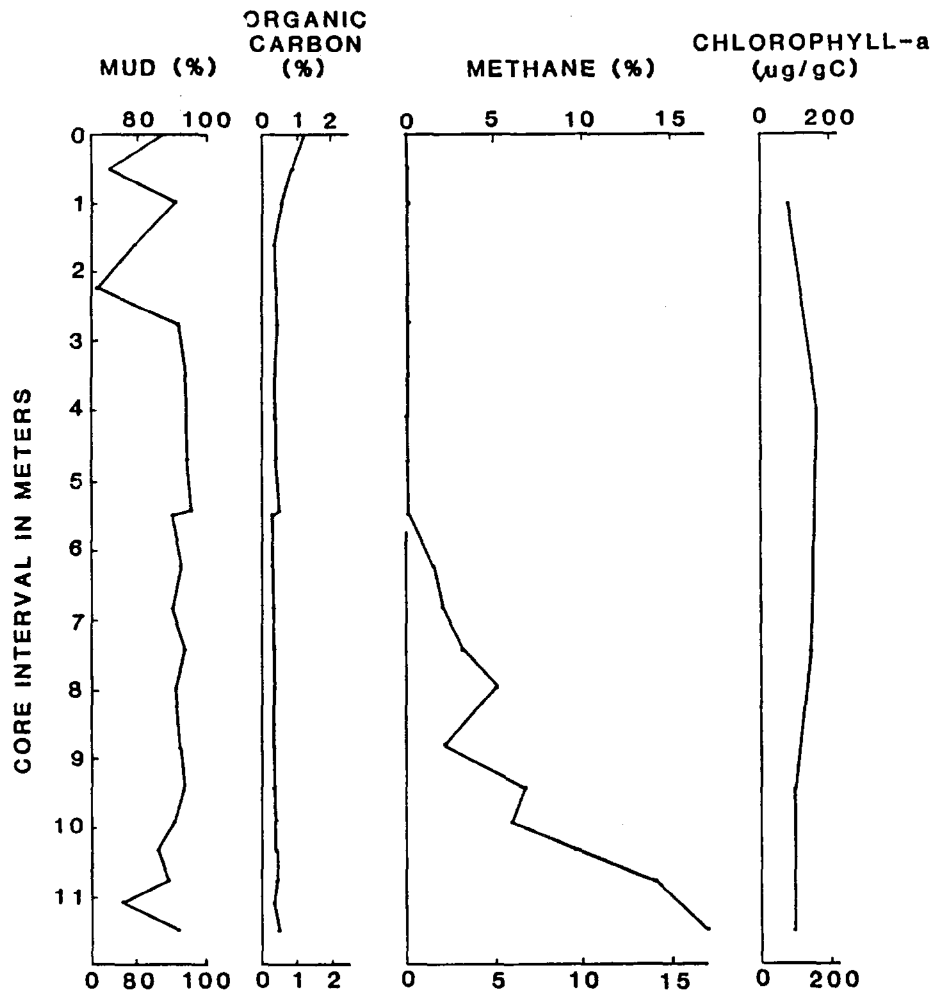


Figure 59. **ORGANIC CARBON, METHANE AND CHLOROPHYLL-A CONTENTS OF LATE PLEISTOCENE MUDS OF SOUTH LABRADOR SHELF (CARTWRIGHT SADDLE)**

Modified after Vilks and Rashid (1977)

The southern extension of the East Newfoundland Basin (Jeanne d'Arc Sub-basin) has been the site of a major oil and gas discovery, Hibernia; other discoveries of smaller magnitude have also been reported from separate structures. Although the Hibernia oil and gas field is in very shallow water (76 to 86 m), similar geologic conditions appear to persist northward into the deeper waters of the East Newfoundland Basin, where pressure conditions are favorable for formation and preservation of gas hydrates. Therefore, the possibility exists for thermogenic gas in this area which may be trapped within or below a hydrate zone.

Slope - Rise

Information regarding stratigraphy and lithology for these environments is sparse. DSDP Site 111 on the continental rise shows the presence of about 150 m of Cenozoic hemipelagic muds, clays and marls, i.e. typical abyssal lithologies, which may contain sufficient organic matter for bacterial methane production. We suggest that the BSR discussed above is probably found in similar lithologies.

It is also important to note that whereas the thin Cenozoic sections of the rise beneath much of the Atlantic margin are underlain by oceanic crust, these sediments adjacent to the Grand Banks are underlain by foundered continental crustal blocks. Thus, the potential exists for hydrocarbon generation from source rocks within these basement blocks. Such generative capability may provide an important source of gas to the hydrate zone beneath the lower slope and rise.

DSDP Site 112 in the Labrador Sea confirmed the presence of turbidite sands in deep water off the continental margin of eastern Canada. Presumably, similar turbidites may exist offshore from Newfoundland, providing a good gas hydrate reservoir lithology. DSDP Leg 112 also indicated that deep-circulating bottom currents have played an important role in distributing fine-grained sediment on the continental rise. Thus, morphologic features akin to outer ridges like the Blake Outer Ridge and Hatteras Outer Ridge from the U.S. continental margin would be potential sites for gas hydrate formation.

Sedimentation Rates

Shelf

Vilks et al. (1974) indicate that the preservation of organic matter in methane-rich surficial sediments of the Labrador Shelf is due to a high sedimentation rate within the Pleistocene sedimentary depressions. The sedimentation rate was sufficient to promote near-surface anoxic conditions. Between these depressions the post-Pleistocene sedimentation has largely involved a redistribution of glacial deposits at a relatively low deposition rate. These areas are unlikely to be optimal for organic matter preservation.

Similarly, the vast shelf area of the Grand Banks is blanketed by a thin veneer of gravelly material markedly poor in organic-rich mud and consequently, without methane generative capacity.

Slope - Rise

High sedimentation rates are required to preserve substantial amounts of marine organic matter on the rise. This has been the case along the Newfoundland and Labrador continental slopes since the late Tertiary. It is also inferred that the high organic productivity associated with many slope environments of the world and especially from the U.S. Atlantic coast was also characteristic of the Newfoundland and Labrador part of the North Atlantic Ocean so that the eastern Canadian continental slope would be a potentially important area for hydrate formation.

Organic Matter

Redox Conditions

By comparison with other parts of the western Atlantic Ocean margin, we conclude that strongly anoxic conditions in the water column did not prevail in this region, except perhaps the widespread Cretaceous anoxic event. Thus, it seems unlikely that muddy sediments with greater than 1.0 - 1.5% TOC will be encountered.

Organic Matter Type

Bujak et al. (1977) show that on the Labrador Shelf (Figure 54) the thick Cenozoic section is dominated by marine kerogen. In contrast, the Mesozoic sediments are dominated by terrestrial organic matter. A similar distribution is encountered for the Grand Banks area (Figures 60 - 64).

Assuming a distribution of organic types similar to the present sediments of the western Atlantic Ocean margin, we then consider the Holocene fine-grained sediments of the shelf and rise to be dominantly terrestrial in origin and a higher proportion of marine types in the slope region. Exceptions may exist in the rise region if turbidity current activity transport marine organic matter into the abyssal environment.

The hummocky seismic pattern of the top sediments of the deep East Newfoundland Basin and Central Labrador Sea can be confidently interpreted in terms of major turbidity mass resedimentation processes which dominated the bathyal realm during the Pliocene - Pleistocene. These sedimentary processes led to a dilution of the autochtonous marine organic matter by a dominant influx of shelf derived terrestrial type organic matter. Also, scant data derived from the DSDP Sites 112 and 113 lend credence to the concept of a glacially derived, current deposited Pleistocene prism of sediments, overall, poor in partly degraded and oxidized organic matter of terrestrial derivation and of consequently of very limited generative capacity.

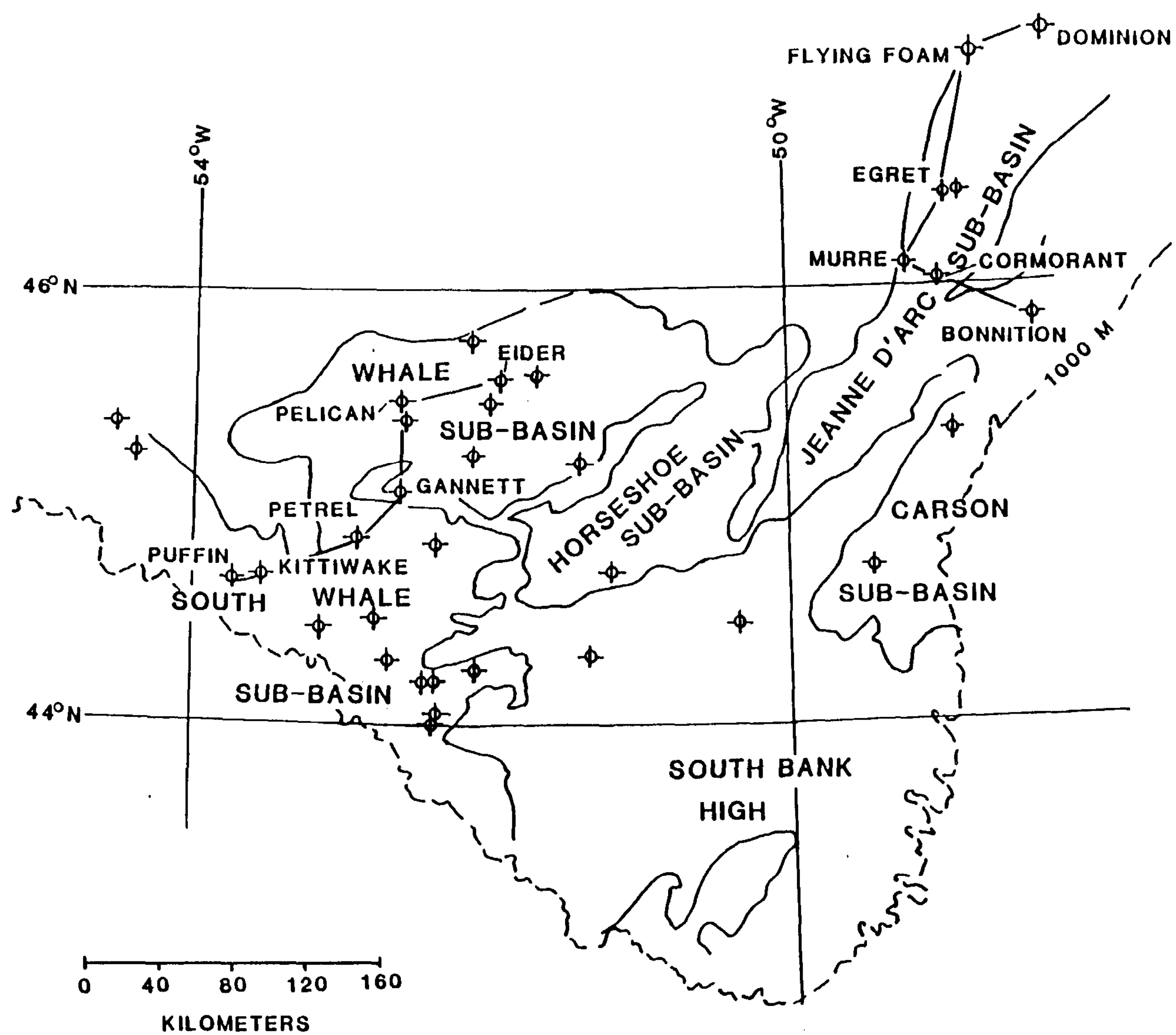


Figure 60. **LOCATION OF EXPLORATORY WELLS, GRAND BANKS ORGANIC MATTER STUDY**

Modified after Swift and Williams (1980)

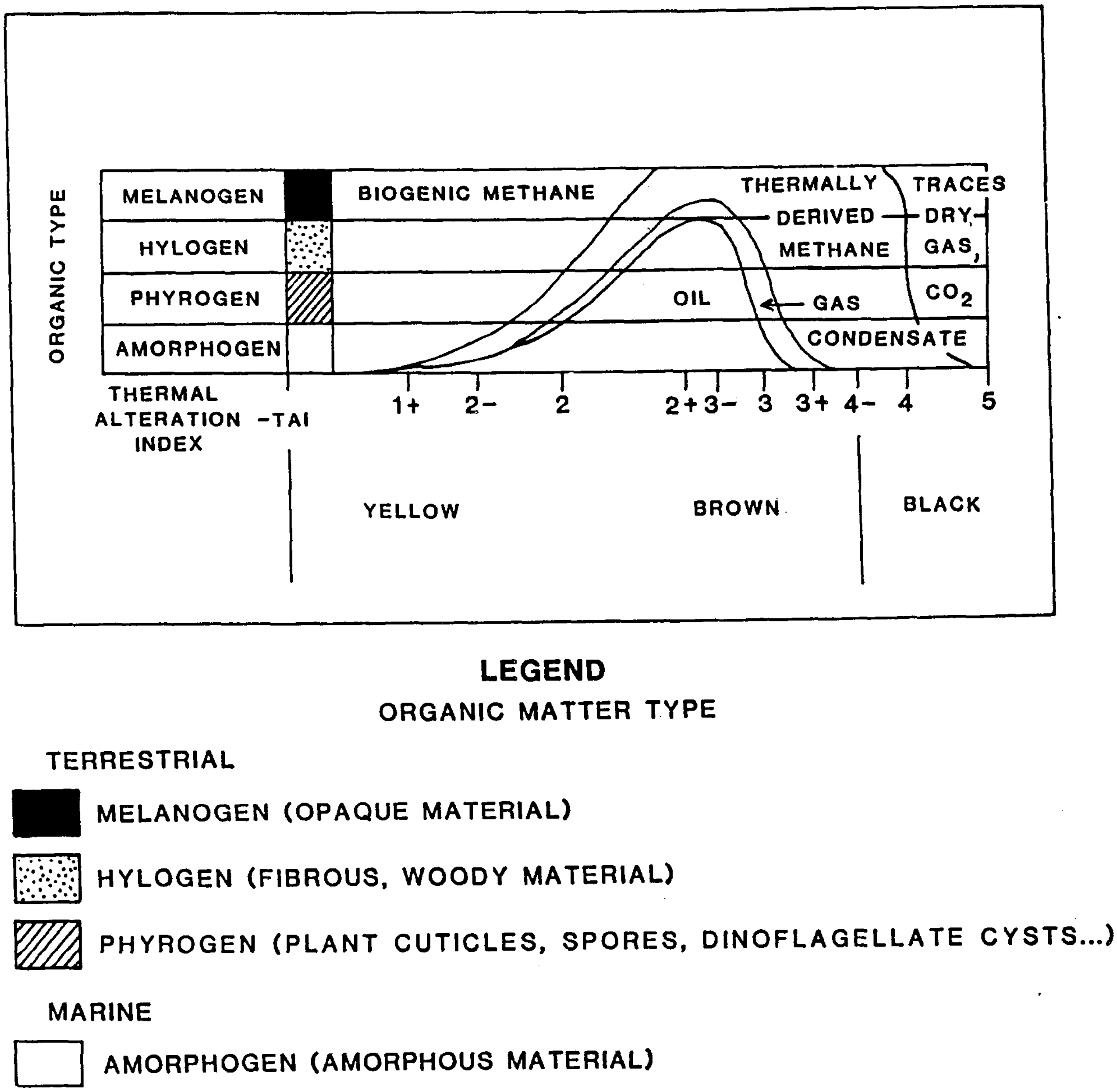


Figure 61. THERMAL ALTERATION OF ORGANIC MATTER

Modified after Bujak et al. (1977)

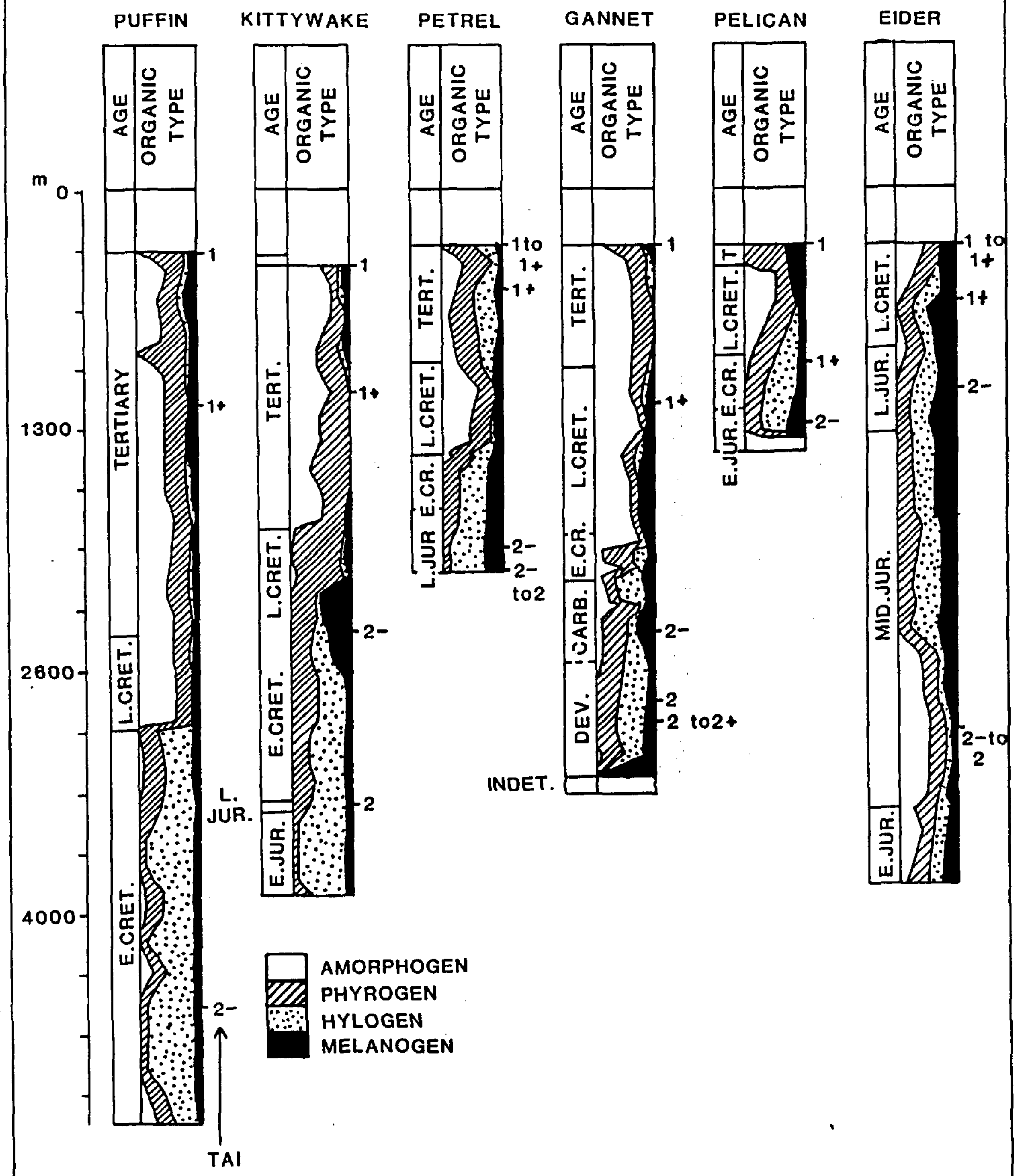


Figure 62. ORGANIC MATTER TYPE AND THERMAL ALTERATION INDEX (TAI) FOR FIVE EXPLORATORY WELLS FROM THE NORTHERN GRAND BANKS

Modified after Bujak et al. (1977)

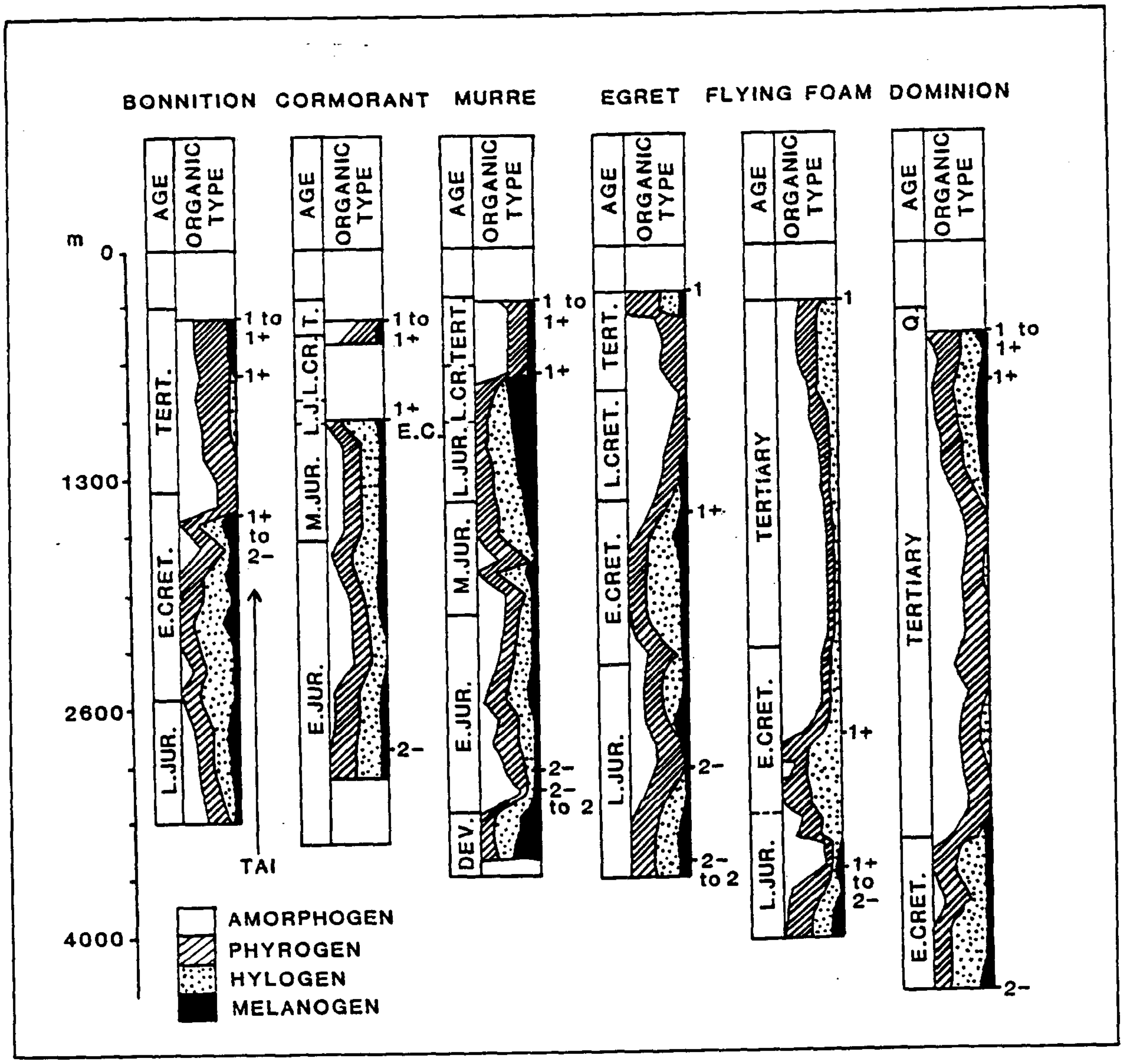


Figure 63. ORGANIC MATTER TYPE AND THERMAL ALTERATION INDEX (TAI) FOR SIX EXPLORATORY WELLS FROM NORTH-CENTRAL GRAND BANKS

After Bujak et al.(1977)

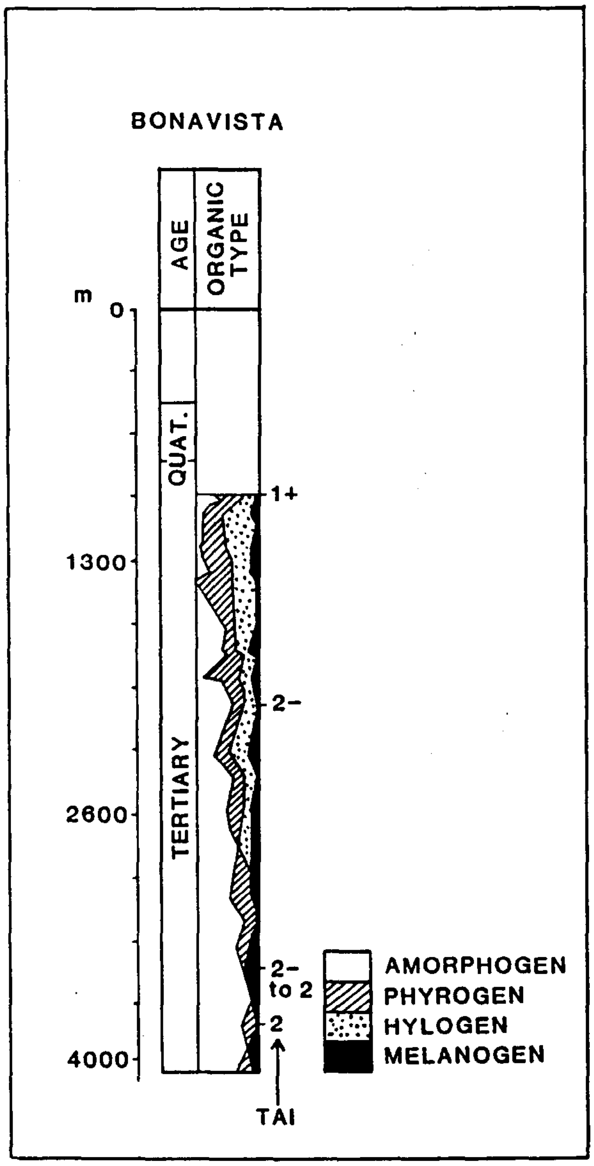


Figure 64. ORGANIC MATTER TYPE AND THERMAL ALTERATION INDEX (TAI) FOR THE BONAVISTA EXPLORATORY WELL

After Bujak et al. (1977)

Sources of Methane

Bacterial Methanogenesis

Vilks et al. (1974) have measured large methane concentrations, up to 16,000 ppm, in Recent sediments trapped in Pleistocene depressions on the Newfoundland Shelf (Figure 57). The purity of the methane led to the conclusion that the gas was produced by microbial reduction of organic matter. Similar processes should exist on the slope and rise under the conditions of sufficiently high sedimentation rate and the availability of sufficient organic matter. Data for these restrictions are presently unavailable.

Thermal Degradation

Bujak et al. (1977) have carried out an examination of the thermal alteration of kerogen found in the Grand Banks, East Newfoundland Basin, and Labrador Shelf (Figures 51, 60, and 64), as an indicator of thermal maturity to petroleum generation. The maturity of parts of the margin is indicated by exploration discoveries and numerous shows of oil and gas on the shelf. Most shelf sediments appear to be either thermally immature or marginally mature, suggesting that petroleum has migrated from the deeper, more mature parts of the basins. It appears that the deeper Jurassic sections together with the underlying Paleozoic sediments, wherever present, are likely to be the most productive sources of hydrocarbons. Geochemical studies of produced oils and condensates (Powell, 1979) also suggest a terrestrial organic source for at least some petroleum, which also implies an early Mesozoic or Paleozoic source.

A source rock potential study of the East Newfoundland Basin and the Labrador Shelf conducted by Rashid et al. (1980), indicates that the Mesozoic - Cenozoic rocks contain high concentrations of organic carbon derived mainly from a terrestrial source, which is usually gas prone (Figures 52 and 53). Consequently, many thick sections in several wells, particularly those located on the northern part of the Labrador Shelf, contain large concentrations of gaseous hydrocarbons. However, the concentrations of heavy hydrocarbons in relation to organic carbon in many of these wells are below the threshold levels for oil occurrences. Thus, their rating for oil is poor. This situation is generally attributed to the organic matter type, which is largely terrestrial, and to insufficient time and temperature for thermal maturation. A few maturity indicators suggest that the organic facies of Cretaceous sediments in the northern Labrador Shelf wells have attained maturity at a depth of about 3,000 - 3,500 m. A marginally mature zone was encountered in some wells, whereas the organic facies of the majority of the wells are still immature.

An extensive discussion of the petroleum potential of the Grand Banks sedimentary basins is provided by Swift and Williams (1980). These authors note the lack of exploration success in the Avalon Uplift of the Grand Banks area and attribute this to a combination of immaturity and poor quality source rocks throughout the Mesozoic and Cenozoic sections. These observations apply to the shelf area, and slightly better source rocks may exist beneath the slope regions. Nonetheless the generally immature nature of source beds beneath the shelf is probably also present beneath the slope. At best, immature gas might be expected beneath the slope regions.

As the sediment wedge thins beneath the rise, the potential for thermally generated petroleum decreases. This was the situation suggested for the Baltimore Canyon Trough region. However, an undetermined thickness of Paleozoic sediments lies beneath the Grand Banks region, in continental crustal blocks subsided to abyssal depths. Thus, the potential exists for petroleum generation within these Paleozoic sediments. Under these circumstances, thermal methane may be present beneath the rise in greater quantities than beneath a more normal rise structure.

Tectonics and Thermogenic Gas

The block-faulted tectonic pattern of the Grand Banks can theoretically be regarded as conducive for the upward migration of thermogenic gas along major or minor fault conduits. The possibility of sub-sea floor gas accumulation under a gas hydrate seal, following a model developed by Dillon et al. (1980), for the offshore eastern U.S. appears feasible but is fraught with difficulties.

Most of the Grand Banks area has been shown by Swift and Williams (1980) to be insufficiently mature for the large scale generation of hydrocarbons and only the northeastern part of the Grand Banks, which is underlain by the Jeanne-d'Arc Sub-basin and the southwestern part, underlain by the South Whale Sub-basin are thermally mature. This has been dramatically confirmed by the recent discoveries of large to giant oil and gas accumulations along the flanks of the Jeanne d'Arc Sub-basin. Given this generative capacity, the Hibernia region, however, is unlikely to follow the Dillon et al. entrapment model for the simple reason that the water depth in this area is insufficient to stabilize gas hydrates (76 to 86 m water depths at Hibernia (Figure 23).

Assuming that similar geologic conditions and hydrocarbon maturation levels occur in deeper water areas peripheral to the Grand Banks (southern East Newfoundland Sub-basin and western Flemish Basin), it remains to be documented that deep thermogenic gas can migrate upward to the sea floor. The block-faulting tectonic event took place during the Early Cretaceous and the faults, granted that the situation documented at the Hibernia oil and gas field can be generalized, do not extend in any significant way upward past the Avalon Unconformity (Figures 22 and 23). The Late Cretaceous and Cenozoic post-rift mega sequence is not faulted and acted as a seal for the deeper structures. Furthermore, this thick blanket of sediments did not reach thermal maturation level on its own (Swift and Williams, 1980). No seismic gas plumes have been reported from seismic profiles. One is left with the concept of shallow biogenic gas production from the late Cenozoic section, which is completely undocumented.

Another type of structure, the salt diapirs, can theoretically provide thermogenic gas access to the upper part of the sedimentary pile. The higher thermal conductivity of salt versus enclosing sediments brings an increase in thermal flux whose effect has been theorized to be responsible for the higher organic matter alteration levels observed or inferred in the encasing rocks (Rashid, 1978; Rashid and McAlary, 1977). This point has been challenged by Keen (1983), who cogently demonstrated that passive thermal effect associated with a salt body is unlikely to cause a significant increase in thermal maturity. However, Keen theorized that migration of hot fluids up the sides and across the top of a salt diapir appears to be the most likely cause of significant increase in the level of thermal maturity within the sediments around the salt. Whatever the preferred model, passive thermal effect versus conductive thermal transfer, a salt diapir can apparently induce a high degree of organic matter maturation at very shallow depth and apparently even hydrocarbon generation (Rashid, 1978; Rashid and McAlary, 1977). Furthermore, the severely disrupted rocks encasing a salt dome are an ideal pathway for the upward migration of deep thermogenic gas. Some of the salt diapirs of the Grand Banks and from the East Newfoundland Basin (Amoco and Imperial, 1973; Cuff and Laving, 1977) reach a high crustal level but, unlike the Blake Ridge region (Grow et al., 1979; Paull and Dillon, 1981), no BSRs have been identified with them (Figure 15).

The previous comments are readily applicable to the East Newfoundland Basin, notwithstanding the notable exception of generally deeper water depth conducive to subbottom gas hydrate stability. Suffice it to say that one of the few wells drilled in this basin (Bonavista well - western part of the basin) tested in its deeper part some rock units which were thermally submature (Purcell et al., 1980; Figure 64).

Similarly, the continental margin off the Labrador Peninsula exhibits the same tectonic evolution as the Grand Banks and East Newfoundland Basin, i.e. an Early Cretaceous rifting phase, widespread block faulting and tilting, concomitant erosion, and differentiated sedimentation, followed by tectonic quiescence. This epeirogenic phase was followed by the deposition of a regionally widespread and uniform, unconformable, thick post-unconformity mega sequence. Good gas shows have been encountered in a number of sub-unconformity structural traps, under the seal provided by the post-unconformity rocks; upward massive leakage from these traps appears limited. Growth faults and shale diapirism localized along former paleoslopes and present day outer shelf and continental slope are appropriate features, theoretically conducive to major sustained upward thermogenic gas migration and entrapment within and under subbottom gas hydrate zones.

Assessment

With no verified proof that gas hydrates occur in the study region, estimation of gas reserves therefrom are highly speculative. Reasonable assumptions of sediment porosity and the degree of pore filling, vertical thickness, and areal extent of gas hydrates in the regions can lead to some preliminary figures.

Continental Margin of Offshore Newfoundland

The water depth over most of the Grand Banks is near the lower limit necessary to stabilize thermogenic gas hydrates in the cold waters found in the region. Since even more severe pressure and temperature conditions are necessary to form hydrates,hydrate occurrences there should be very rare. Only where hydrocarbon seeps are active will the necessary supersaturation be attained to form and stabilize hydrates. We estimate that less than 0.1% of the 300,000 km^2 would have the necessary structural disturbance over mature generative basins for large-scale seepage. Such a hydrate zone would be thin (< 100 m). Assuming 40% sediment porosity and 12% of the pore space filled by gas hydrates, 5% of the sediment volume would be gas hydrates. Kuuskraa et al. (1983) estimate a 200:1 volume conversion of gas at standard conditions from gas hydrates.

The amount of gas present over the entire area of the Grand Banks in a 1 m gas hydrate zone consistent with these assumptions is:

$$1 \text{ m thickness} \times 3 \times 10^{11} \text{ m}^2 \text{ area} \times 5\% \text{ hydrates}$$
$$\times\ 0.1\% \text{ areal extent} \times 200 \text{ volume conversion factor} =$$
$$3 \times 10^9 \text{ m}^3 \text{ (0.1 TCF)}$$

The volume of gas contained in a hydrate zone of various mean vertical extent would be:

$$1 \text{ m} = 3 \times 10^9 \text{ m}^3 \text{ (0.1 TCF)}$$
$$10 \text{ m} = 3 \times 10^{10} \text{ m}^3 \text{ (1 TCF)}$$
$$100 \text{ m} = 3 \times 10^{11} \text{ m}^3 \text{ (10 TCF)}$$

The remainder of the Newfoundland continental margin includes areas more favorable for gas hydrates. The water depths in the Flemish Basin, Newfoundland Ridge, and J-Anomaly Ridge are sufficient to stabilize biogenic and thermogenic hydrates (Figure 1). The Newfoundland Ridge is underlain by a 20,000 km^2 sub-unconformity basin similar to those which contain mature thermogenic source rocks under the Grand Banks (Figures 12 and 17). Thus, thermogenic gas hydrates are also possible if migrational routes exist. Therefore, a much larger probable areal extent of gas hydrates of 1% is estimated for the 200,000 km^2 Newfoundland continental margin exclusive of the Grand Banks.

For a 1 m thick gas hydrate zone consistent with all these assumptions, the area-wide gas volume would be:

$$1 \text{ m thickness} \times 2 \times 10^{11} \text{ m}^2 \text{ area} \times 5\% \text{ hydrates}$$
$$\times\ 1\% \text{ areal extent} \times 200 =$$
$$2 \times 10^{10} \text{ m}^3 \text{ (0.7 TCF)}$$

Gas volumes contained in the area for a hydrate layer of various mean thickness are:

$$1 \text{ m} = 2 \times 10^{10} \text{ m}^3 \text{ (0.7 TCF)}$$
$$10 \text{ m} = 2 \times 10^{11} \text{ m}^3 \text{ (7 TCF)}$$
$$100 \text{ m} = 2 \times 10^{12} \text{ m}^3 \text{ (70 TCF)}$$

East Newfoundland Basin and the Southernmost Labrador Shelf

The 200,000 km^2 area of the East Newfoundland basin and the southernmost Labrador Shelf is under water deep enough to stabilize gas hydrates.

Sub-unconformity basins of unknown organic richness and piercement structures are inferred to exist under portions of this area which may permit the formation of thermogenic hydrates. A probable areal extent of gas hydrate deposits of 1% is assigned to this area.

Using the equation developed above, possible gas volumes contained in gas hydrate zones of various mean vertical extents are:

1 m $= 2 \times 10^{10}$ m^3 (0.7 TCF)
10 m $= 2 \times 10^{11}$ m^3 (7 TCF)
100 m $= 2 \times 10^{12}$ m^3 (70 TCF)

Offshore Labrador

The Labrador Shelf is dissected by numerous small canyons which are deep enough to stabilize. From two of these channels Vilks et al. (1974) cored sediments rich in biogenic methane which displayed degassing characteristics which have come to be associated with gas hydrates. Also, the Labrador Shelf and upper continental slope are underlain by deep thermally mature Mesozoic potential source rocks. Of the 120,000 km^2 area of the continental shelf and slope offshore of Labrador, only 90,000 km^2 is sufficiently deep (270 m) to stabilize biogenic gas hydrates in sediments beneath the very cold water. We estimate that 7.5% of the area may be underlain by gas hydrates of biogenic or thermogenic origin.

The volumes of gas contained in sediments of the Labrador Shelf and continental slope for different assigned mean vertical extents of hydrate development are thus:

1 m $= 7 \times 10^{10}$ m^3 (2.5 TCF)
10 m $= 7 \times 10^{11}$ m^3 (25 TCF)
100 m $= 7 \times 10^{12}$ m^3 (250 TCF)

We discovered a possible BSR in rifted sediments in the deep Labrador Sea (Figure 58). The seismic sections reveal that such sedimentary prisms in the province of terriginous sedimentation (Figure 57) are rare. The area also lacks the depths of sediments necessary for thermogenic gas generation. Therefore, we assign a probably areal extent of gas hydrates in the 300,000 km^2 area to be 1%.

Volume of methane contained in gas hydrate beneath the deep water of the Labrador Sea calculated at 5% gas hydrates by volume is 3 x 10 m (1 TCF) per meter thickness. For gas hydrate layers of varying mean area-wide thickness, the total gas contained in hydrates under the Labrador Sea would be:

1 m $= 3 \times 10^{10}$ m^3 (1 TCF)
10 m $= 3 \times 10^{11}$ m^3 (10 TCF)
100 m $= 3 \times 10^{12}$ m^3 (100 TCF)

Data Gaps

1. Lack of high quality seismic data in the public domain from which BSRs could be recognized.

2. Lack of available data from:
   - seismic profiles
   - well logs on slope and rise
   - geochemistry (organic and inorganic)
   - cores

These are necessary to assess stratigraphy, pore-fluid geochemistry, gas sources, TOC, sediment physical properties, for the slope-rise region.

Future Evaluation

The following studies should be included in any future program designed to assess the hydrate potential of this region.

1. A detailed study of the Pleistocene sedimentary depressions on the continental shelf and upper continental slope, as potential gas hydrate sites.

2. A study of the continental slope-rise regions for morphologic features akin to outer ridges of the U.S. continental margin, as regions of high sedimentation rate and potential gas hydrate sites.

3. A multi-channel seismic profiler program to identify BSRs, thus allowing a mapping of the areal extent of the hydrate zone. Alternately, a study of industry's seismic data if made available.

4. A focused study of the continental slope and associated deep basins as potential gas hydrate-bearing zones in order to facilitate possible recovery technology.

5. A deep water drilling program specifically designed to test the gas hydrate potential along similar lines to DSDP Leg 76, once the presence of gas hydrates has been confirmed from seismic data.

6. An attempt to interrogate industry regarding unusual drilling experiences that may have been associated with the presence of hydrates.

Conclusions

Based purely on the pressure and temperature stability field of gas hydrates, very large oceanic areas (in water deeper than 600 m approximatively) offshore of Newfoundland and Labrador are theoretically favorable for gas hydrate stability. But the formation of gas hydrates requires the availability of methane within the pore systems of the sea floor sediments.

Thermogenic methane migration from deep seated reservoirs to the near sea floor sedimentary environment has been considered at some length in this report and appears to not be likely on a wide scale. The hydrocarbon generative strata and associated potential reservoirs are regionally sealed by a widespread post-unconformity sequence, breached only by salt diapirs. It is estimated that the periphery of high level diapiric structures may offer the best possible geologic setting for thermogenic methane occurrence at near sea floor level.

Biogenic methane production by in-situ bacterial fermentation within the top portion of the sedimentary column appears to represent a more likely possibility. It requires the presence of a moderately high amount of reactive, nonoxidized organic matter and a reducing pore environment conducive to bacterial methanogenesis.

The continental slope off the seaward margin of the continent appears to offer the best possibilities. Higher marine organic production in conjunction with high sediment rate are favorable factors. This report went through some length to define the geology and geographically complex configuration of the continental slope which includes large, unexplored basins (East Newfoundland Basin, Flemish Basin). Due to the lack of data pertaining to the continental slope, extrapolation of continental shelf geology and recent sedimentary patterns was used to assign an overall favorable gas hydrate potential to these areas.

The Grand Banks of Newfoundland does not offer great potential for gas hydrate occurrences. Its peripheral margins, the Flemish Basin and the East Newfoundland Basin should present a reasonable potential. The only seismic BSR reported in the literature from the entire offshore region of Eastern Canada apparently occurs in a continental slope setting, at the margin of the East Newfoundland Basin.

The Labrador continental slope appear to present the best potential for gas hydrates. Data from the outer shelf when extrapolated to the continental slope are encouraging: reduced, gas-bearing muddy sediments, marine organic matter and right pressure and temperature parameters.

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